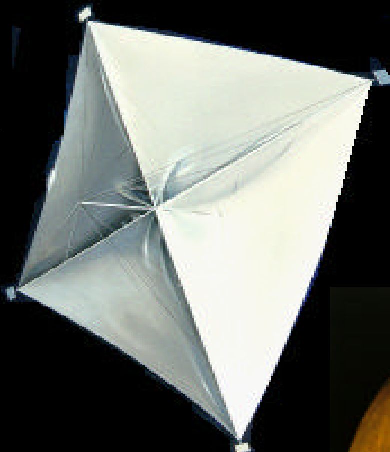
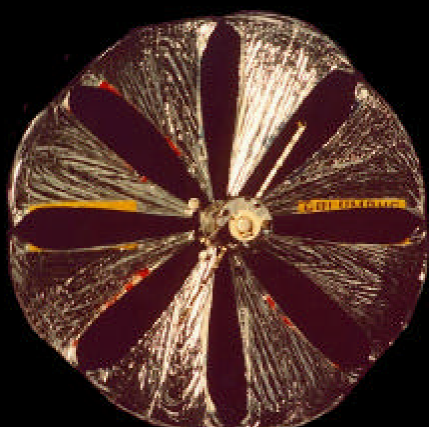
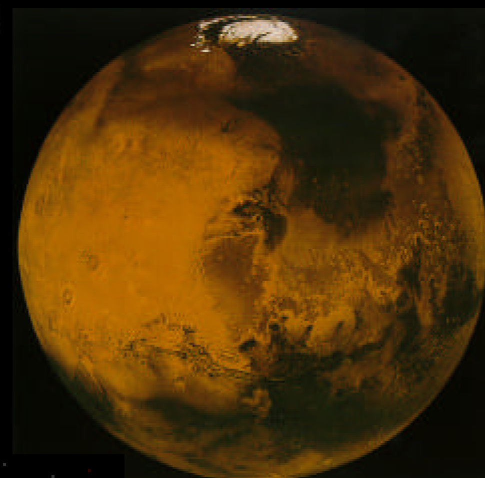
SOLAR AND ELECTROMAGNETIC SAILS FOR THE MARS CARGO MISSION



3-Axis Square Solar Sail



Rotating Disk Solar Sail (Znamya)



M2P2 Electromagnetic Sail (Znamya)

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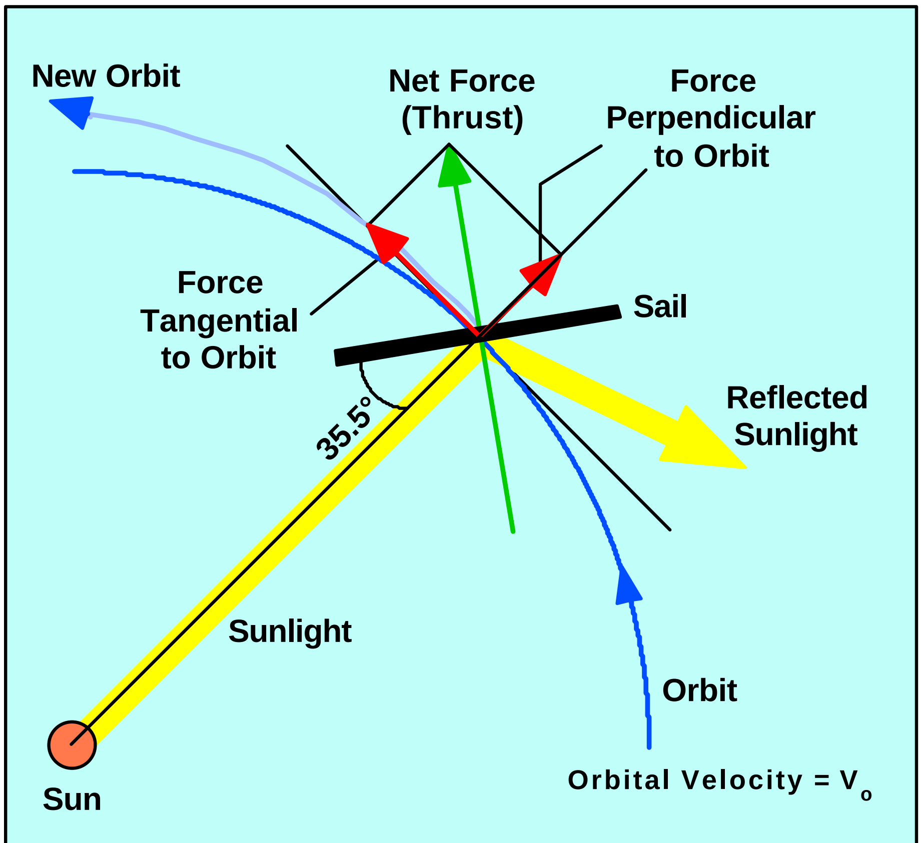
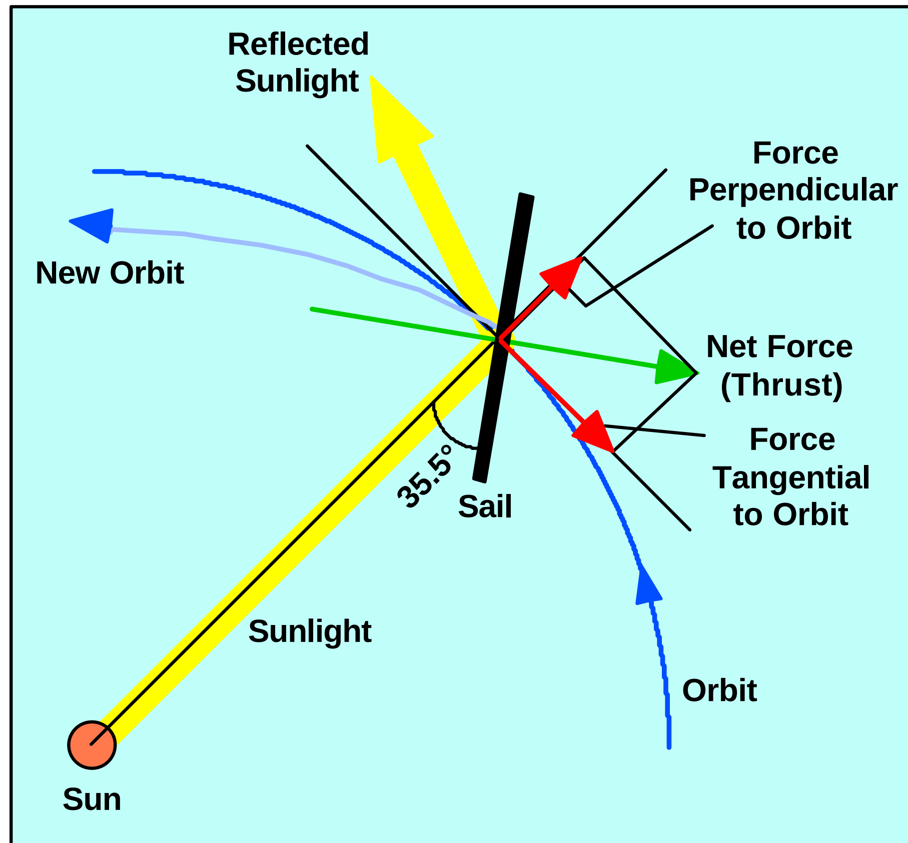
SOLAR SAILS

- Solar Sails use photon "pressure" or force on thin, lightweight reflective sheet to produce thrust: Ideal reflection of sunlight from surface produces 9 Newtons/km^2 (5.2 pounds/mile^2) at 1 AU (drops off as $1/R^2$)
- Net force on solar sail perpendicular to surface
- One component of force always directed radially outward
- Other component of force tangential to orbit (Add/subtract to V_o)

Sail Moves Away from Sun



Sail Moves Towards Sun



SOLAR SAILS FOR THE MARS CARGO MISSION

MISSION SCENARIO

- Solar Sail mission starts in 400 km LEO (Each Sail carries 1 Mars Lander)
  - Two sizes of Landers: 58 MT and 72 MT
- Sail plus Cargo (Mars Lander) boosted to 2000 km circular orbit by Chem stage
  - 2000 km alt. minimizes air drag - MAY be possible to operate Sail as low as 1000 km
- Sail (w/ payload) transfers to heliocentric Mars orbit (Vinfinity=0)
  - Optional: Sail transfers to low circular Mars orbit
- Sail (empty) returns to 2000 km Earth orbit for re-use

SAIL TRAJECTORY CALCULATIONS

- Trip times a function of Characteristic Acceleration (Ac, mm/s^2), which is determined from Total Sail + Payload Areal Density (g/m^2=MT/km^2 of Sail area)
  - Lower Areal Density -> Lower Trip Time AND Lower IMLEO (for a given Sail area)
  - Heliocentric transfer calculated by Carl Sauer (JPL)
  - Earth and Mars escape/capture spirals calculated by method of Sands

    Sands, N., "Escape From Planetary Gravitational Fields by Use of Solar Sails," <u>American Rocket Soc. J.</u>, Vol. 31, April 1961, pp. 527-531.
- <u>Total</u> IMLEO = Sail + Payload + Chem Stage (wet) Masses, plus dry mass of any Lander and Chem Stage propellant Tankers required to transport propellants to LEO

SAIL TECHNOLOGY CONSIDERATIONS

- What is achievable Total Sail (film, structure, etc.) Areal Density
  - Vary Sail Areal Density from 10 g/m^2 (near-term) to 0.1 g/m^2 (interstellar mission)
- How big a sail can we make, deploy, use (Bigger sail reduces Sail+Payload Areal Density)
  - Vary Sail area from Nominal (required to meet trip time constraints) ± 5 km^2

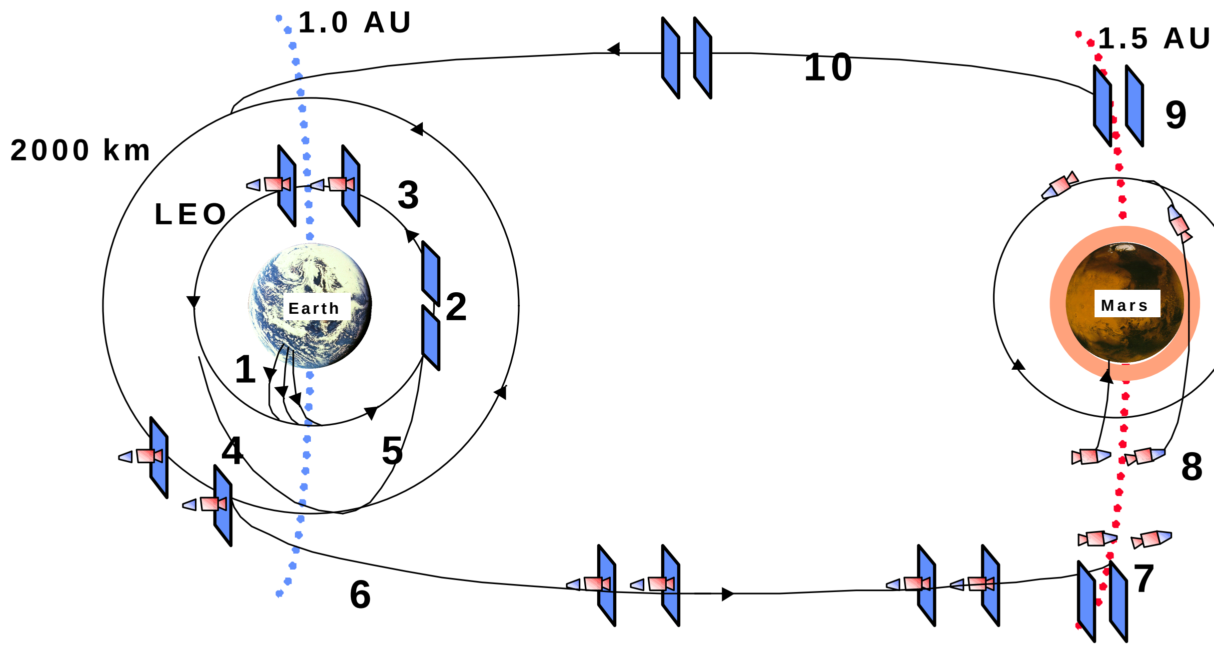
THREE MARS CARGO OPTIONS

- Assume Sail transports Mars Lander (only) one opportunity (ca. 2.1 years) prior to crew departure
  - Cargo required to arrive at Mars prior to next Crew Earth departure

- Goal is to separate Cargo mission from Crew mission so as to combine Sail Cargo mission with any of the various Crew mission options
  - Crew mission contains all elements required to ensure safe return of crew in case of failed Mars orbit rendezvous with pre-deployed cargo (Mars Landers)

- Three types of Mars Landers possible (data from Bret G. Drake, JSC)
  1. Aerobraked Descent Lander with Ascent Vehicle (to 500 km circular Low Mars Orbit, LMO) and Short-Stay (30 Day) Surface Habitat: 57.511 MT
  2. Aerobraked Descent Lander with Ascent Vehicle (to 1-Sol 250x33,793 km High Mars Orbit, HMO) and Short-Stay (30 Day) Surface Habitat: 72.140 MT
  3. Aerobraked Descent Lander with Long-Stay (580 Day) Surface Habitat (but no Ascent Vehicle): 58.237 MT
  - Landers 1 or 2 appropriate to fast (1-year) crew missions
    - Lander (1 or 2 w/Ascent Stage) aerobrakes into Crew rendezvous orbit (Eliminates Sail Mars capture spiral time)
  - Lander 3 (plus Lander 1 or 2) needed for slow (minimum energy) crew missions
    - Lander 3 (w/ Surface Hab.) aerobrakes to surface, second Lander (1 or 2 w/Ascent Stage) aerobrakes into Crew rendezvous orbit (Eliminates Sail Mars capture spiral time)

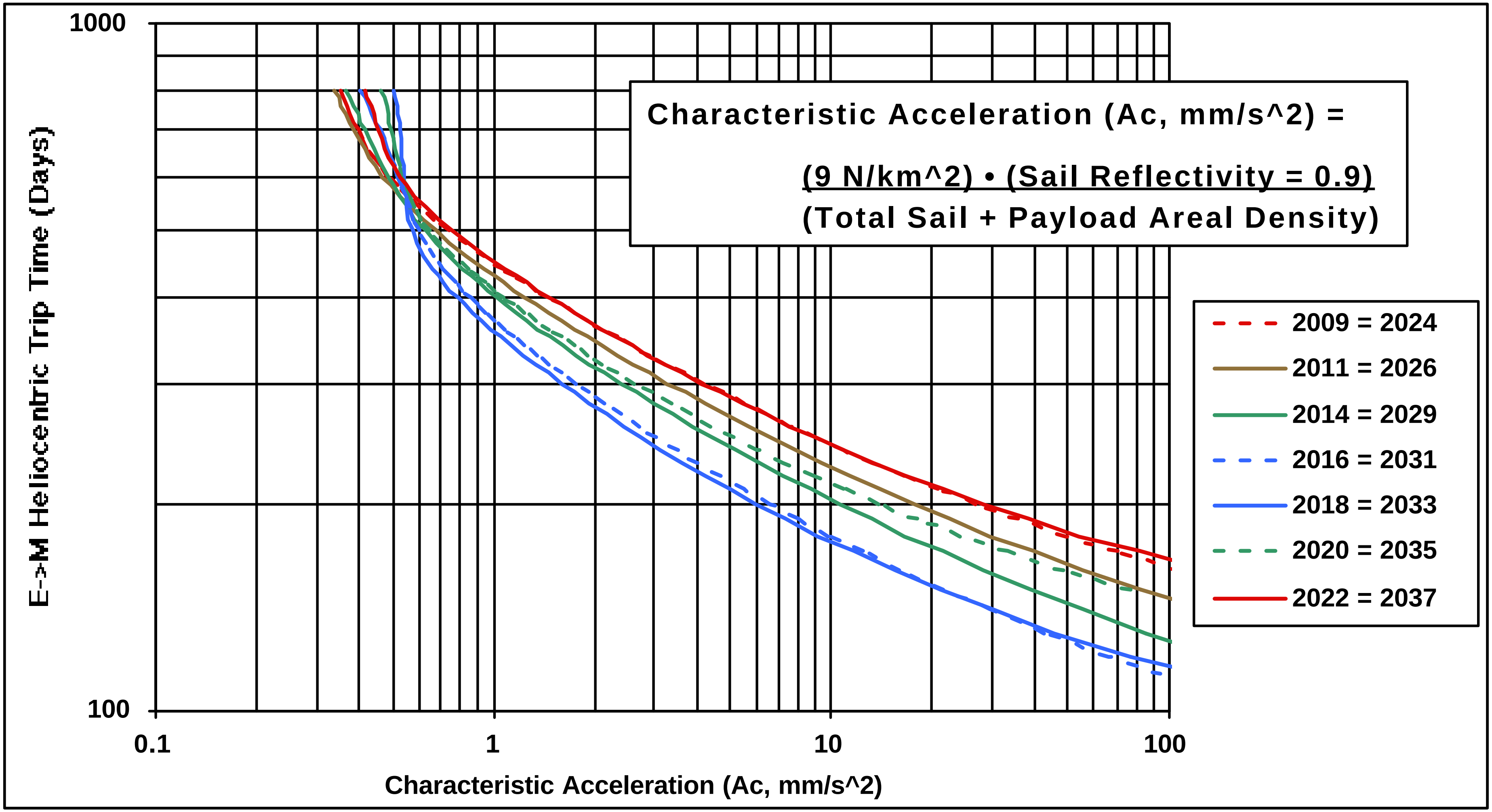
SOLAR SAIL CARGO MISSION EVENT SEQUENCE



1. Launch 1-2 each Sails, Cargo (Landers), LEO->2000km Chem Stages (w/ propellant) into LEO (multiple launches)
2. Deploy / erect Sail in LEO ("Feather" Sail to minimize air drag)
3. Assemble cargo vehicle systems (1-2 vehicles) by mating 1 Cargo Lander with 1 Sail
4. Use 1 each Chem Stage to transfer 1 each Sail+Cargo vehicle into 2000 km circular Earth orbit
5. Chem Stages returns to LEO (for re-use)
6. Sails (w/ Cargo) begin Earth escape spiral, then perform heliocentric transfer to heliocentric Mars orbit (1.5 AU)
7. Cargo (Landers) separate from Sails on Mars approach (Vinfinity~0)
8. Landers aerobrake into Mars
   - Lander w/ Ascent Vehicle aerobrakes into Mars orbit to await rendezvous with Piloted vehicle
   - Lander w/ Long-Stay Surface Habitat aerobrakes to Mars surface (for long missions)
9. Sails loiter in Mars heliocentric orbit (to await Earth return opportunity)
10. Sails perform heliocentric transfer to heliocentric Earth orbit, then perform Earth capture spiral (into 2000 km Earth orbit)

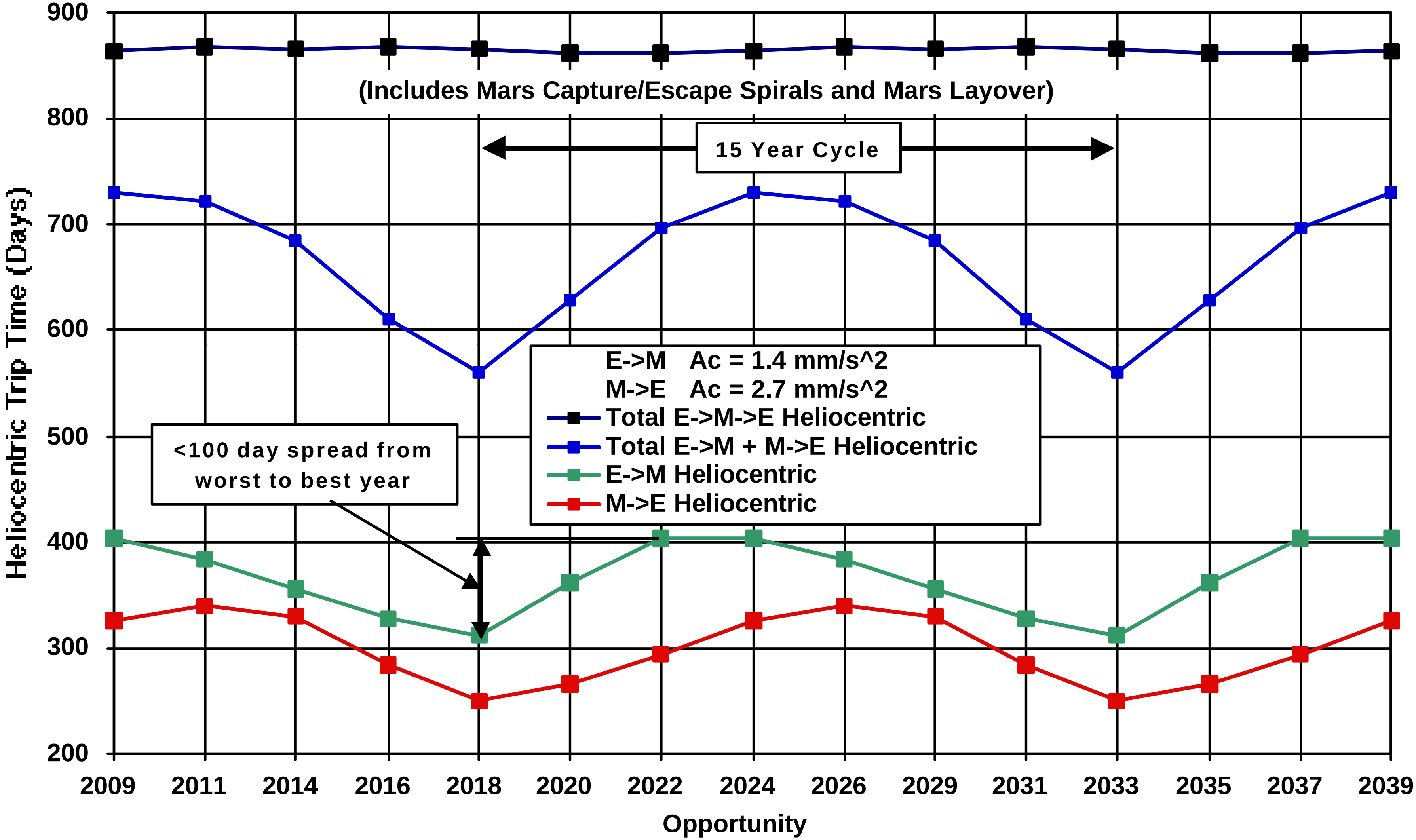
SOLAR SAIL HELIOCENTRIC TRIP TIME VS CHARACTERISTIC ACCELERATION (Ac)

- Evaluated 2007-2039 opportunities for impact on trip time
  - Trajectories repeat every 14.95 years: 2007=2022, 2009=2024, etc.
  - Data shown for Earth->Mars (E->M) heliocentric transfer
  - Trajectory data tend to become unstable for Ac<0.6 mm/s^2



SOLAR SAIL TRAJECTORIES ILLUSTRATE "GOOD" & "BAD" MARS MISSION YEARS

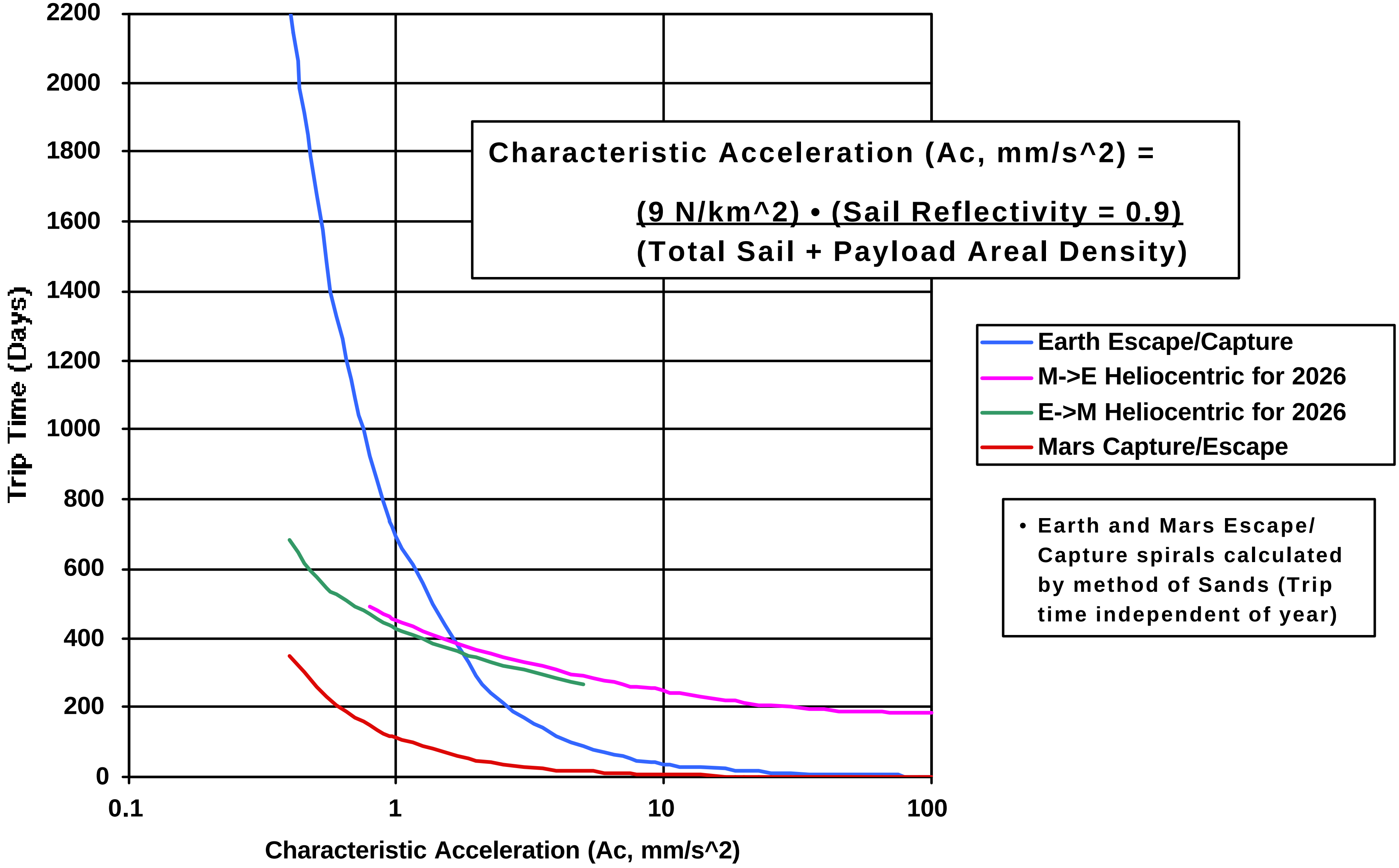
- Worst year (longest trip time) 2024/26, best year (shortest trip times) 2018, ave. year 2014
  - Data shown for Ac values for "Nominal" Sails



SOLAR SAIL CALCULATION METHODOLOGY

- Select "Worst" year (2026)
- Pick Payload mass (one 58-MT or one 72-MT Mars Lander per Sail)
- Vary Sail areal densities about "nominal" value
  - 3.0 g/m^2 = MT/km^2 (Sail film, structure, miscl. systems, etc., but not Payload) selected as nominal value (1 g/m^2 C-C film [only] already produced by ESLI)
  - Vary areal density parametrically 0.1-10 g/m^2
- Vary Sail area (size) about "nominal" value
  - For the nominal Sail area value, pick a Sail area (by trial-and-error) that gives an Ac that makes it possible to deliver Cargo payload to Mars before next Crew Earth departure (~2.1 years), and also makes it possible for the Sail to return (empty) to Earth (2000 km circ. Orbit) before the next Sail Earth departure (~4.2 years)
    - Opportunity 1: Sail departs Earth
    - Opportunity 2: Sail arrives at Mars before Crew leaves Earth
    - Opportunity 3: Sail returns to Earth, picks up next payload, and departs
  - For a Sail areal density of 3 g/m^2, nominal Sail areas are:
    - 20 km^2 for Lander 1 or 3 (58 MT), 25 km^2 for Lander 2 (72 MT)
  - Vary Sail area parametrically ± 5 km^2 about nominal value
- Calculate Sail mass based on Sail area and areal density
- Determine TOTAL (Sail+Payload) vehicle mass and corresponding Ac
  - Determine Sail trajectory trip times as a function of Ac
- Add Chem LEO->2000 km Stage and Earth-to-Orbit (ETO) propellant "Tankers" for total Initial Mass in LEO (IMLEO)

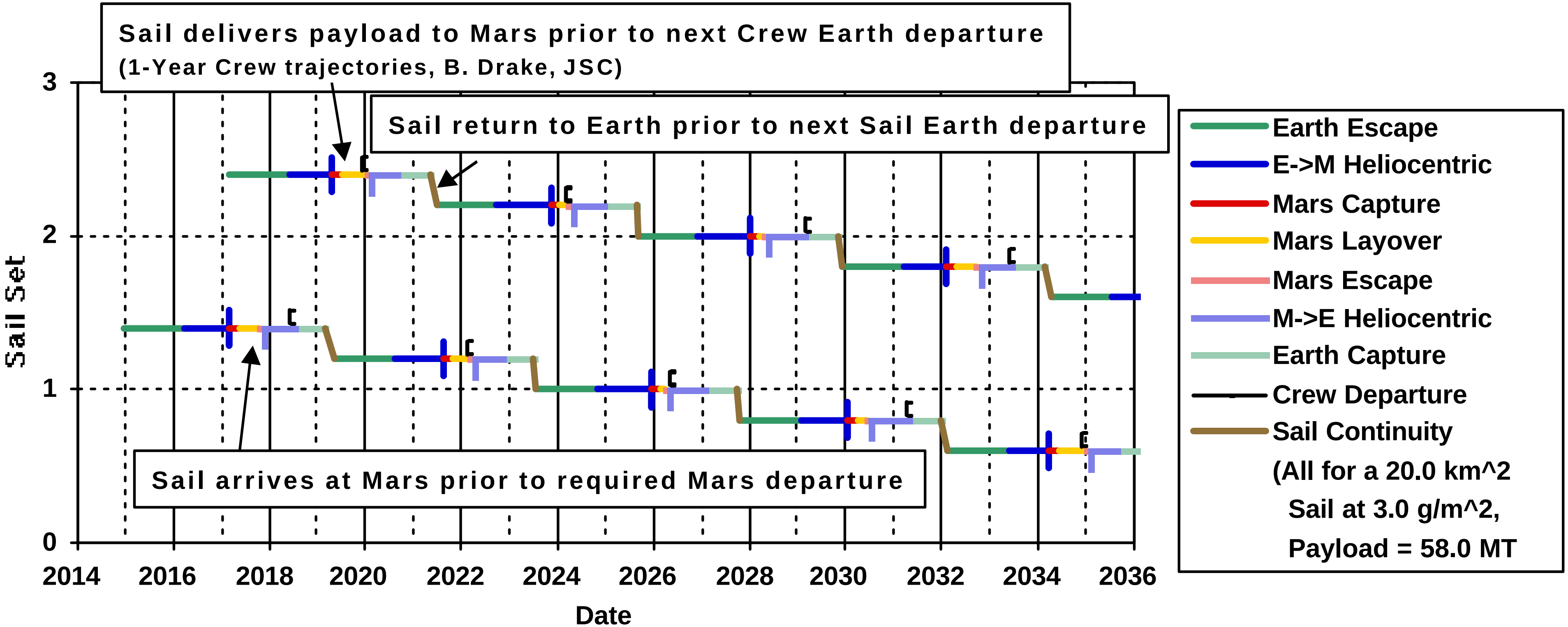
SOLAR SAIL TRIP TIME VS CHARACTERISTIC ACCELERATION (Ac)



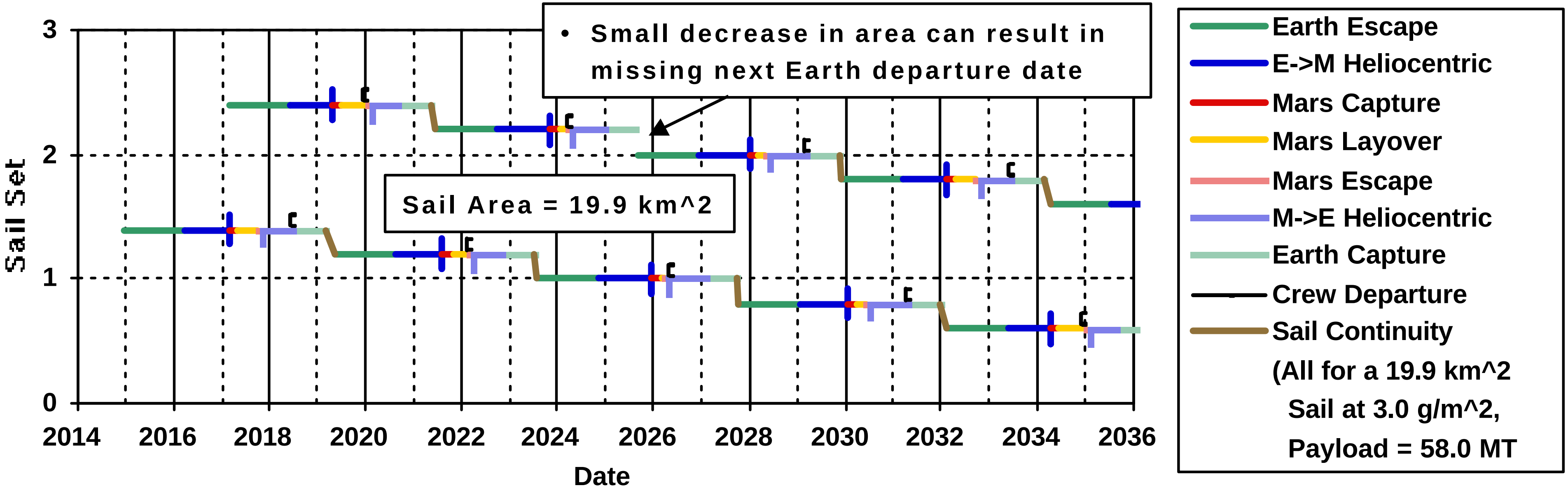
- Earth and Mars Escape/ Capture spirals calculated by method of Sands (Trip time independent of year)

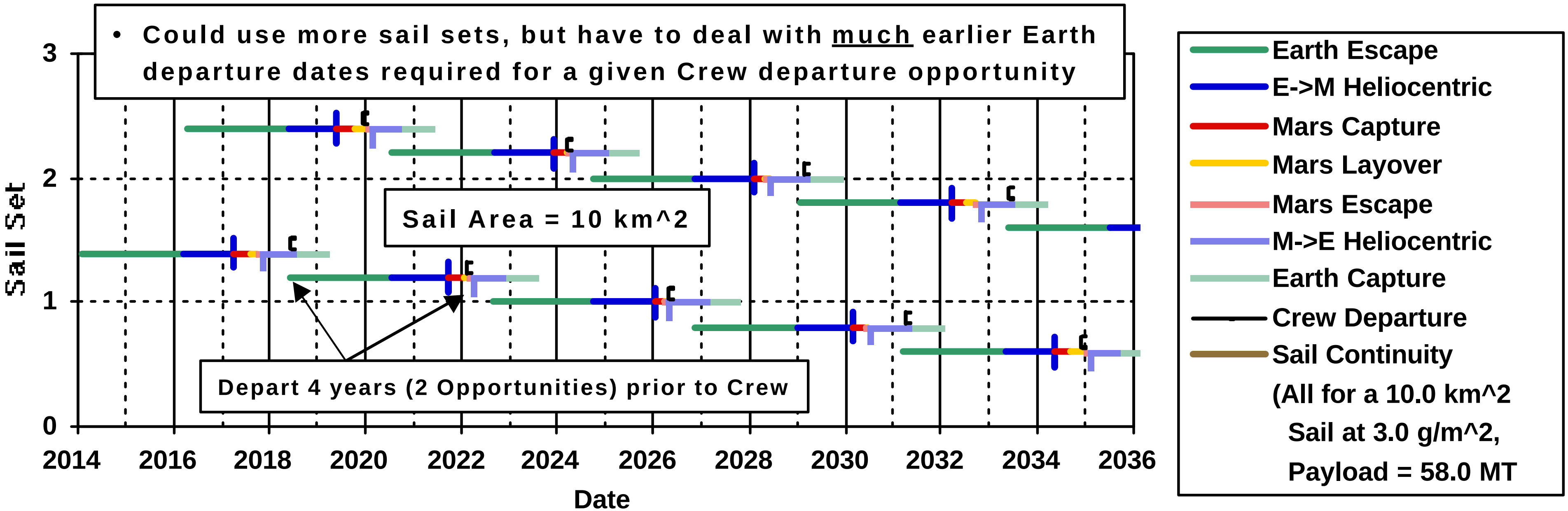
DEFINING "NOMINAL" SOLAR SAIL AREA
(AS A FUNCTION OF Ac FOR 58-MT PAYLOAD)

- Example of selecting Sail area (for a given payload and Sail areal density) that satisfies time-phasing constraints for two sets of sails :
  - Sail delivers payload to Mars prior to next Crew Earth departure date (B. Drake, JSC)
  - Sail arrives at Mars prior to required Mars departure
    - In some years, these two constraints preclude Mars capture/escape spiral time, driving requirement that payload be dropped off in Mars heliocentric space
  - Sail return to Earth in time to pick up new payload and begin next E->M Cargo mission
- For Nominal Sails, E->M Ac=1.4 mm/s^2 and M->E Ac=2.7 mm/s^2 to meet schedule

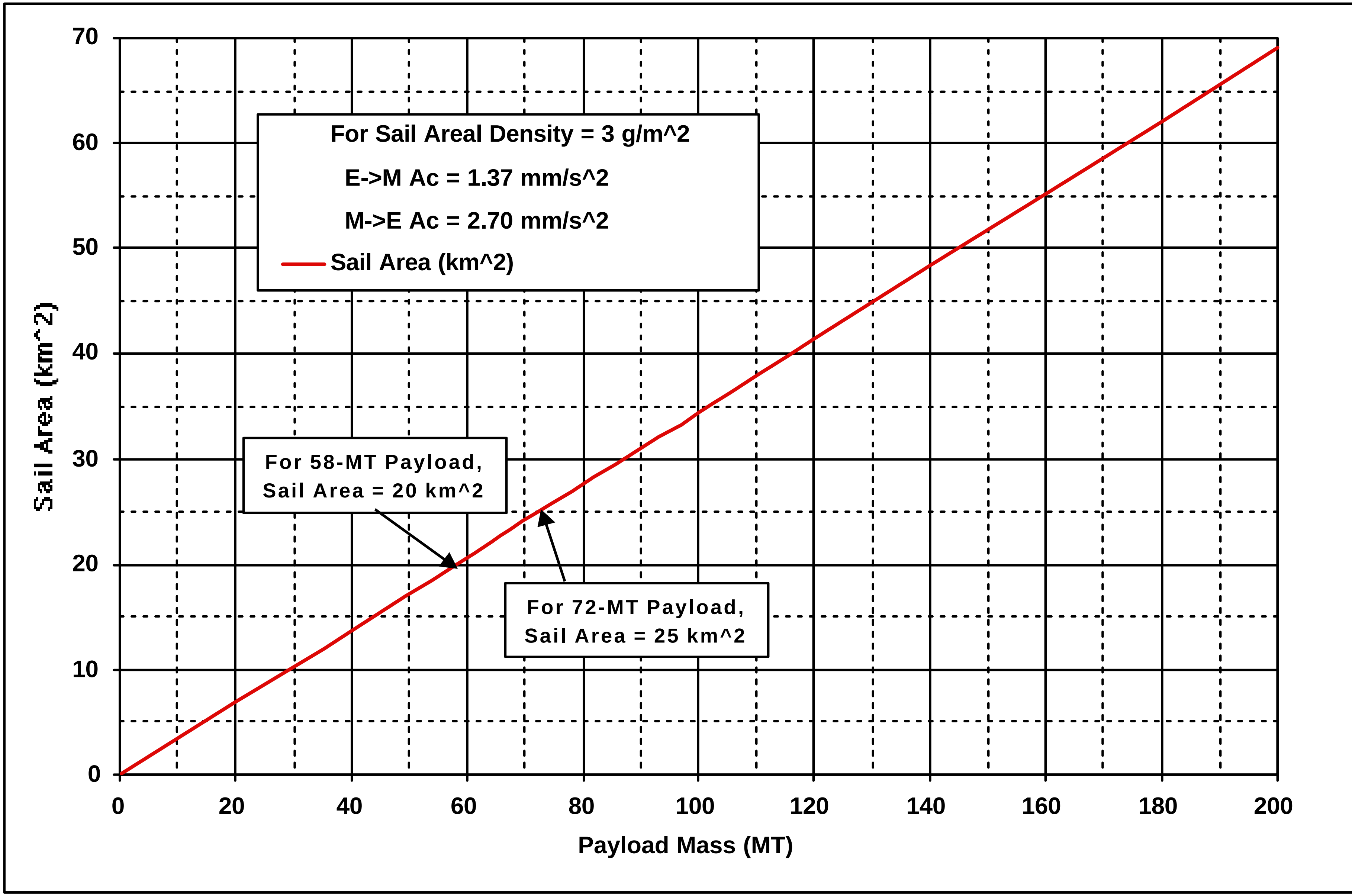


MISSION TIMELINE SENSITIVE TO SOLAR SAIL AREA (AND CORRESPONDING Ac)



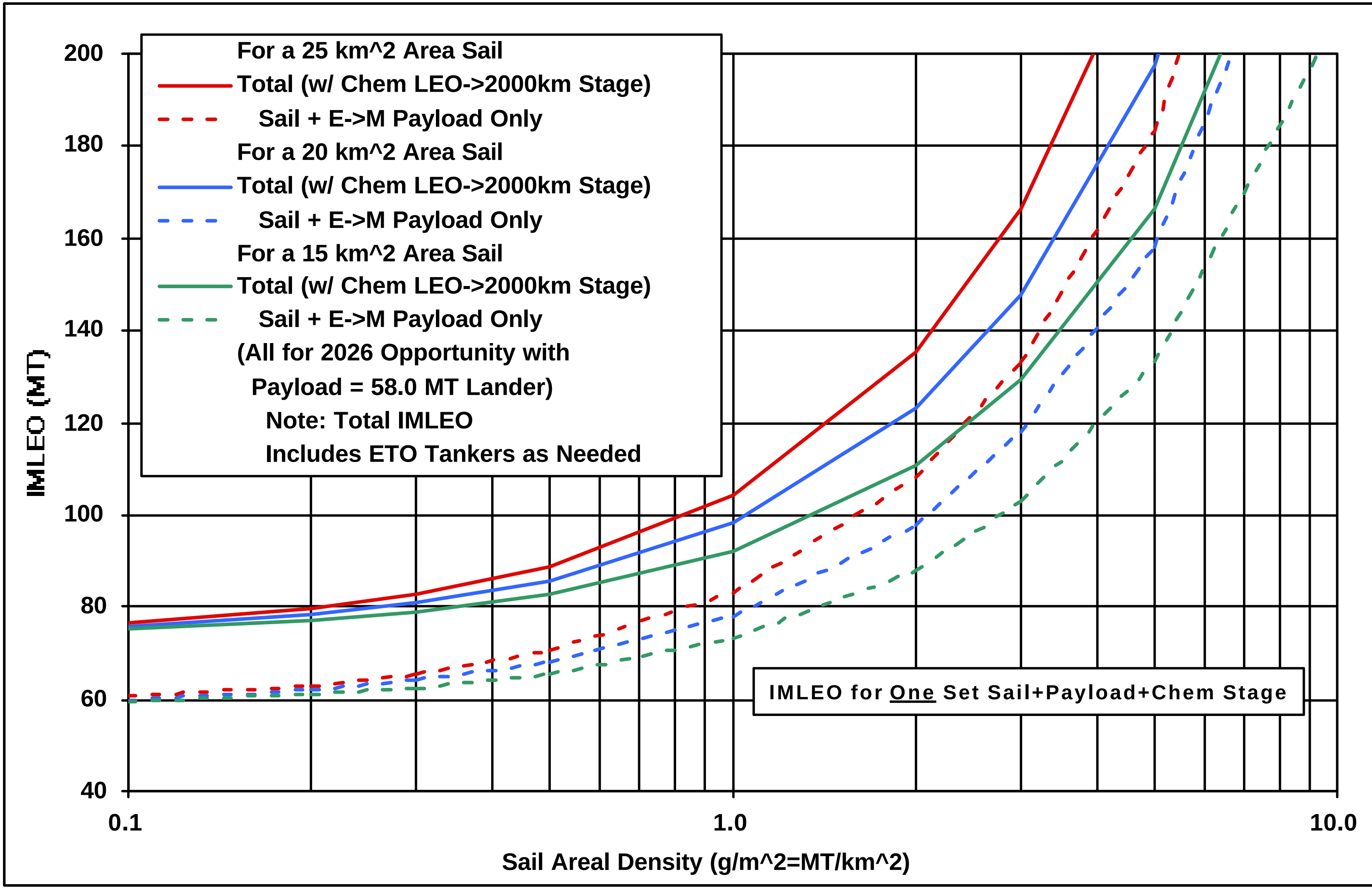


SOLAR SAIL AREA VS PAYLOAD MASS TO MEET MISSION TIMELINE CONSTRAINTS



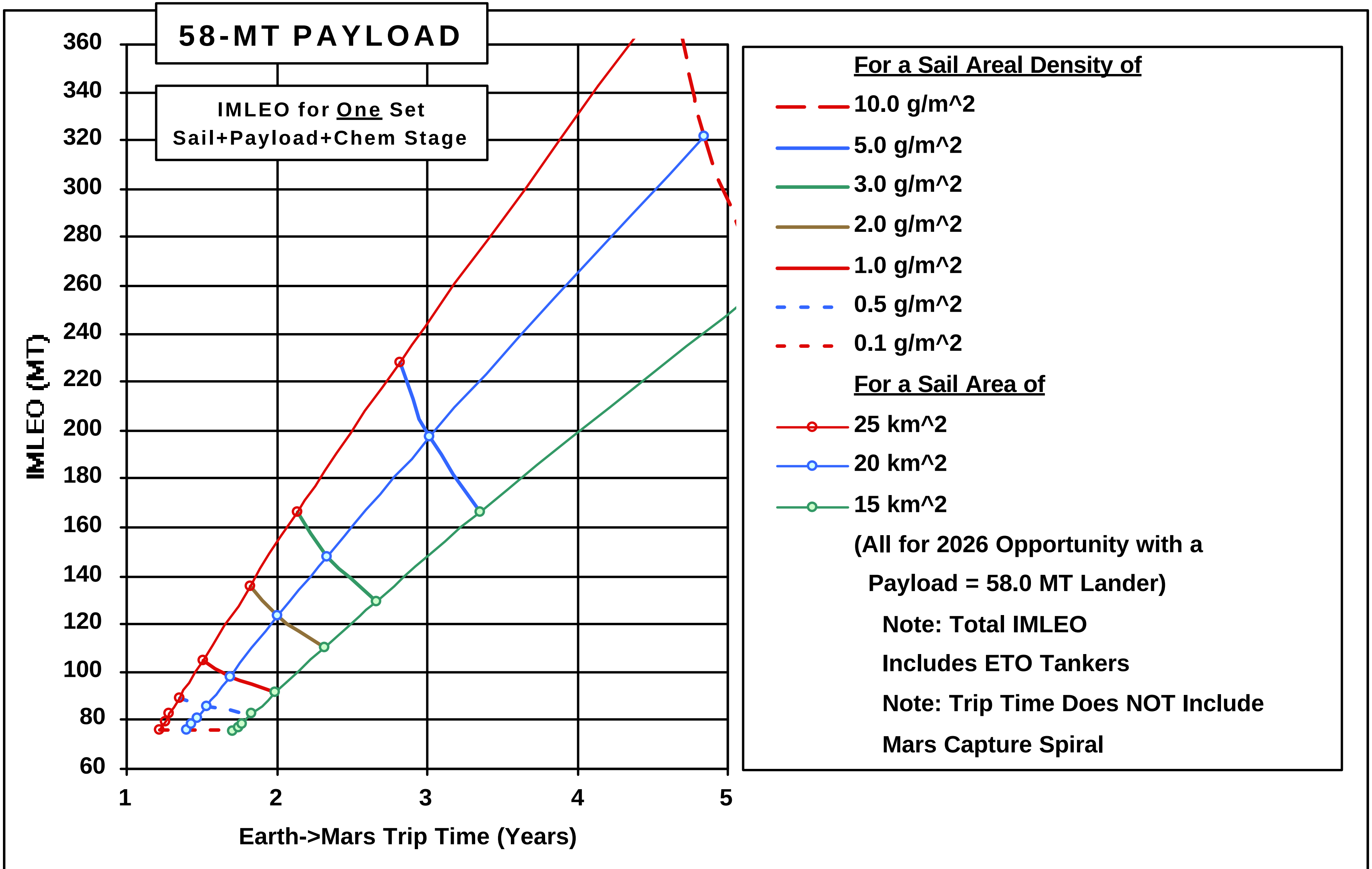
SOLAR SAIL IMLEO VS AREAL DENSITY

(AS A FUNCTION OF SAIL AREA FOR 58-MT PAYLOAD)



SOLAR SAIL IMLEO VS TRIP TIME

(AS A FUNCTION OF SAIL AREA & AREAL DENSITY)

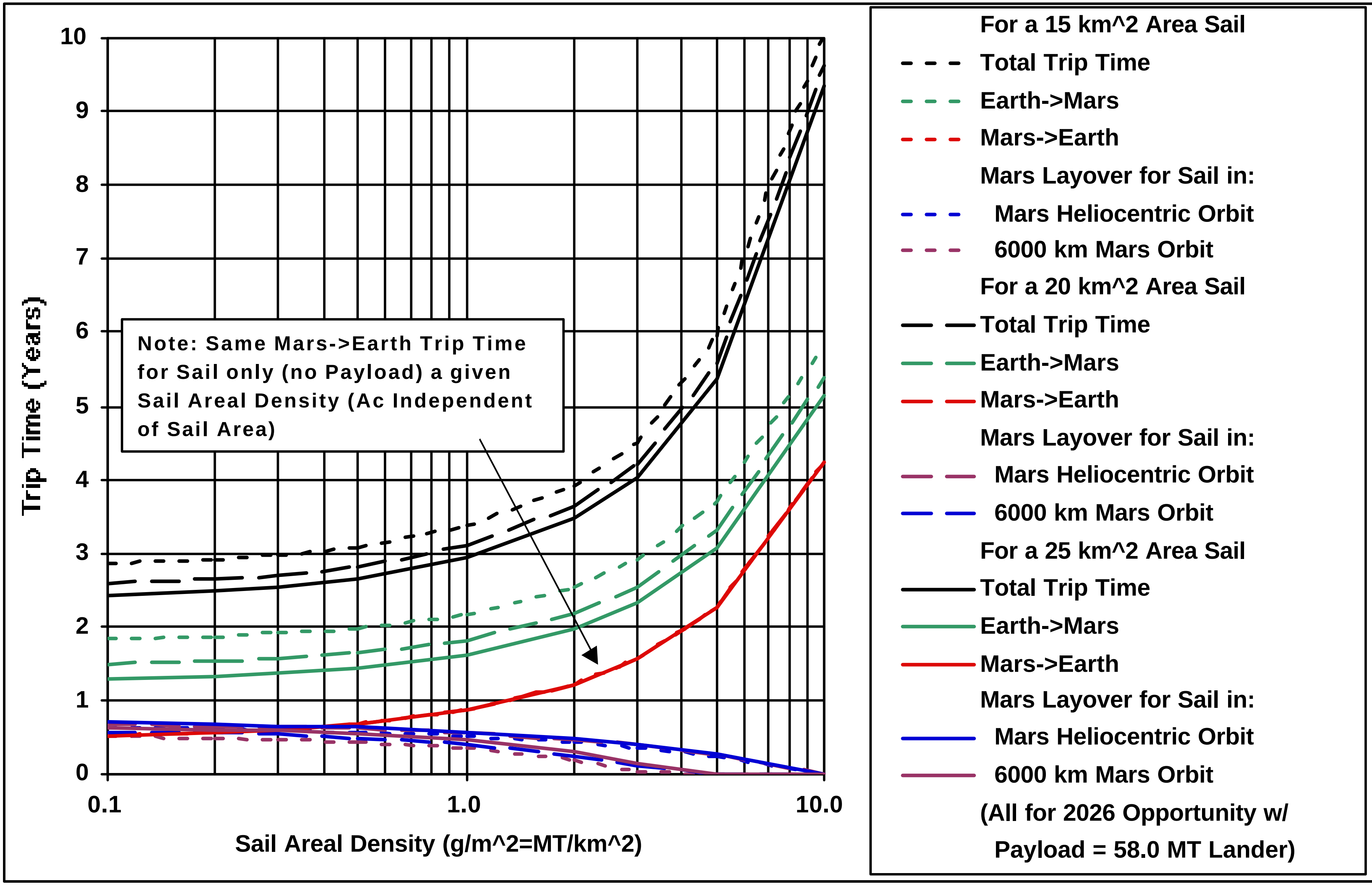


SOLAR SAIL SYSTEM TIMELINE AND MASS EXAMPLE (57.5 MT PAYLOAD)

20-km^2, 3.0-g/m^2 Sails, 57.511-MT Descent/Ascent (LMO) Lander	DATE	IMLEO	(MT)
• Setup for First Mars Opportunity	10/28/2014	Sail	60.0
• First set of Sail and Lander launched into LEO	(L1 - 60 Days)	Lander (Wet)	57.5
• Chem Stage launched into LEO		Lander Tanker (Dry)	1.0
• Lander & Chem Stage Tankers (Wet) launched into LEO		Chem Stage (Dry)	3.9
• Sail deployed, Sail+Lander transported to 2000 km		Chem Propellants	24.3
• Chem Stage returns to LEO for re-use		Chem Tanker (Dry)	1.5
		Subtotal	148.2
• First Mars Opportunity (L1)	L1		
• First set of Sail+Lander departs Earth	12/27/2014		
• Setup for Second Mars Opportunity	01/05/2017	Sail	60.0
• Second set of Sail and Lander launched into LEO	(L2 - 60 Days)	Lander (Wet)	57.5
• Lander & Chem Stage Tankers (Wet) launched into LEO		Lander Tanker (Dry)	1.0
• Sail deployed, Sail+Lander transported to 2000 km		Chem Propellants	24.3
• Chem Stage returns to LEO for re-use		Chem Tanker (Dry)	1.5
		Subtotal	144.3
• First set of Sail+Lander arrives at Mars	02/26/2017		
• Lander aerobrakes into required orbit	(Crew Departure - 473 Days)		
• Second Mars Opportunity (L2)	L2		
• Second set of Sail+Lander departs Earth	03/06/2017		
• Crew departs Earth	06/15/2018		
• First set of Sail returns to Earth (2000 km orbit)	03/07/2019	Lander (Wet)	57.5
• Setup for Third Mars Opportunity	(L3 - 63 Days)	Lander Tanker (Dry)	1.0
• Lander, Lander & Chem Stage Tankers launched into LEO		Chem Propellants	12.8
• Lander transported to 2000 km, attached to Sail		Chem Tanker (Dry)	0.8
• Chem Stage returns to LEO for re-use		Subtotal	72.0
• Second set of Sail+Lander arrives at Mars	04/21/2019		
• Lander aerobrakes into required orbit	(Crew Departure - 237 Days)		
• Third Mars Opportunity (L3)	L3		
• First set of Sail+Lander departs Earth	05/09/2019		
• Crew departs Earth	12/15/2019		
• Second set of Sail returns to Earth (2000 km orbit)	05/11/2021	Lander (Wet)	57.5
• Setup for Fourth Mars Opportunity	(L4 - 43 Days)	Lander Tanker (Dry)	1.0
• Lander, Lander & Chem Stage Tankers launched into LEO		Chem Propellants	12.8
• Lander transported to 2000 km, attached to Sail		Chem Tanker (Dry)	0.8
• Chem Stage returns to LEO for re-use		Subtotal	72.0
• First set of Sail+Lander arrives at Mars	08/13/2021		
• Lander aerobrakes into required orbit	(Crew Departure - 185 Days)		
• Fourth Mars Opportunity (L4)	L4		
• Second set of Sail+Lander departs Earth	06/23/2021	Total for 4 Cargo Missions	436.5
• Crew departs Earth	02/15/2022	Ave. per Cargo Mission	109.1

SOLAR SAIL TRIP TIME VS AREAL DENSITY

(AS A FUNCTION OF SAIL AREA FOR 58-MT PAYLOAD)

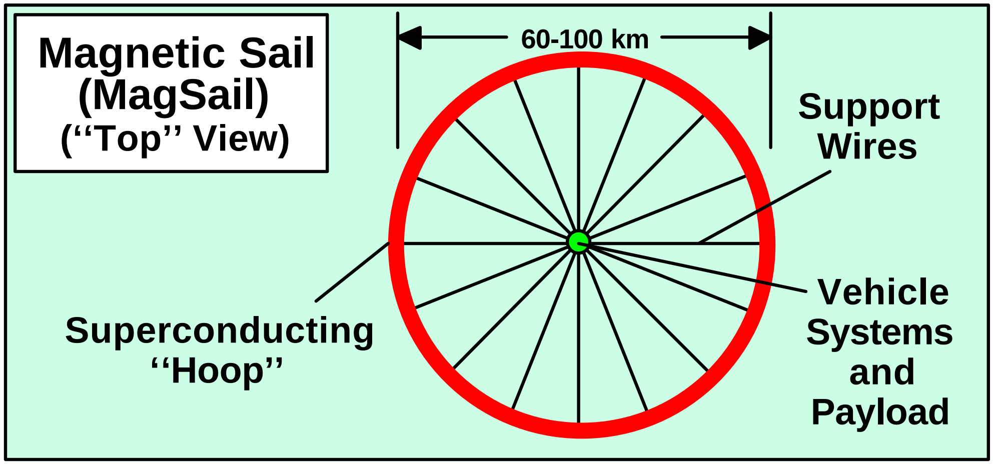


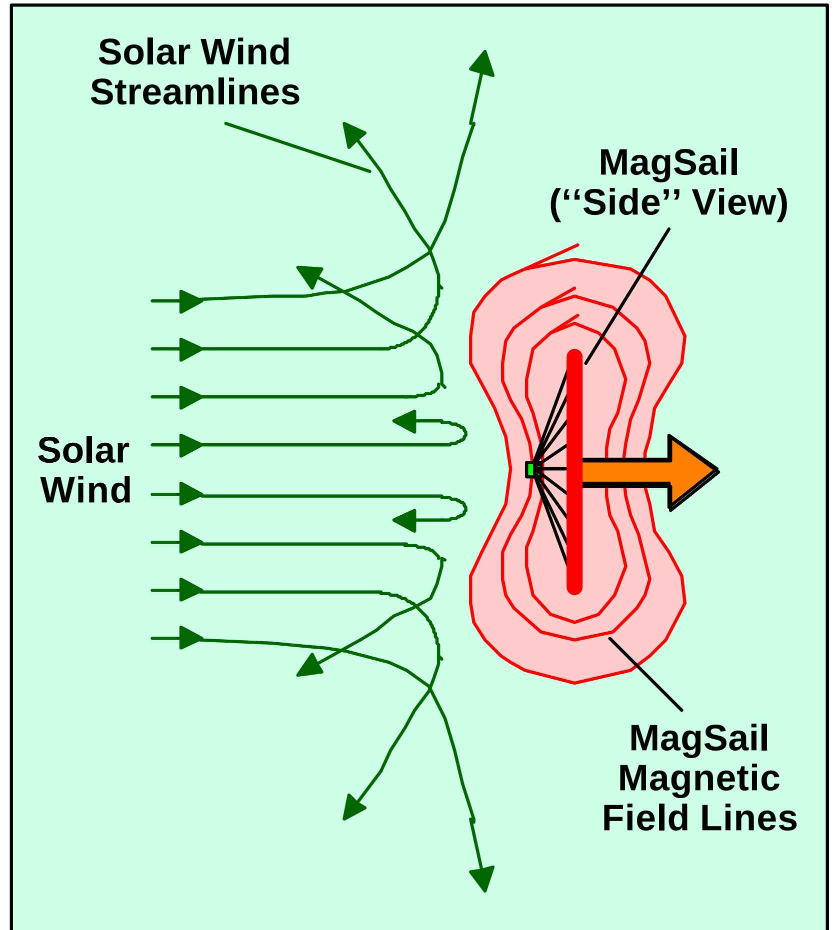
SUMMARY FOR SOLAR SAILS

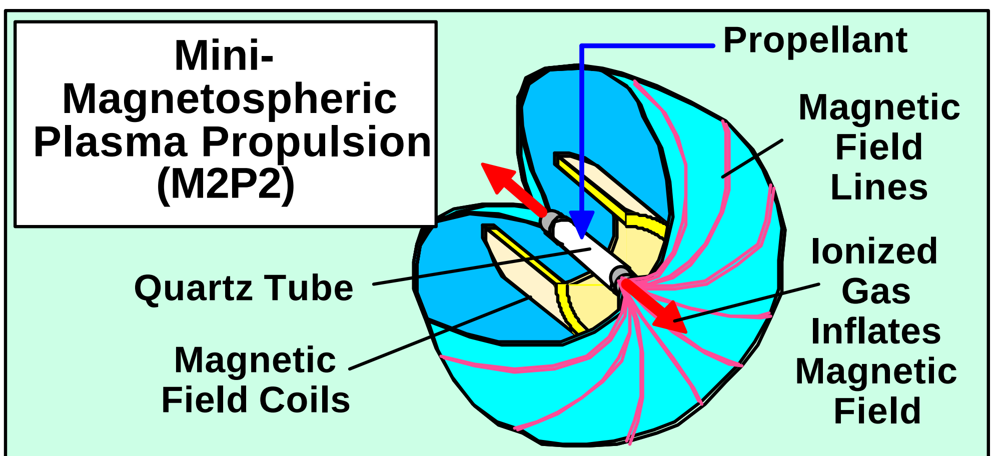
- Solar Sails are a highly mass-efficient "propellantless" Mars Cargo transportation system
  - Solar System "Supertanker" - Slow, but VERY mass efficient
    - Transportation system (Sail+Chem Stage+Tankers) mass ~1.6 x payload mass (for nominal Sails with areal density = 3 g/m^2)
      - 0.9 x payload mass for an "amortized" system (2 missions per sail)
  - Reusable (But total system would require 2 sets of Sails, 1 set per opportunity)
  - Synergistic with many robotic missions
    - Technology Roadmap leading to interstellar missions
- Major technology issues (Sail areal density, deployment, size, etc.) being addressed for robotic missions
  - Advanced C-C sail fabrics (ESLI), ultra-thin plastic films
  - Deployment by C-C booms (DLR) or inflatable struts, or by spinning (Znamya)
  - Large size (~4-5 km) required for Mars Cargo mission comparable to size required for laser-driven 0.1-c interstellar flybys

ELECTROMAGNETIC SAILS

- Electromagnetic Sails use solar wind ion force on a magnetic "wall" to produce thrust
  - Magnetic Sail (MagSail) - Zubrin and Andrews
    - Generates mag. (10^{-5} Tesla) barrier by superconductor ("Wall" dia >> loop dia.)
  - Mini-Magnetospheric Plasma Propulsion (M2P2) - Winglee
    - Uses ionized gas to "inflate" magnetic field to very large sizes







ELECTROMAGNETIC SAILS COMPARED TO SOLAR SAILS

- **Electromagnetic Sails:**
  - **Need to transport EM Sail and Mars Cargo payload to C3=0 (heliocentric space)**
    - M2P2 can operate inside Earth's magnetosphere (10 Re, 57,400 km alt.) via orbit "pumping"
      - Requires rapid magnetic field charge/discharge (analogous to Solar Sail changing orientation relative to sun)
    - MagSali can't - Long time needed for magnetic field charge/discharge
  - **Have mostly radial thrust (limited tangential thrust)**
    - May be difficult to do Mars (1.52 AU) orbit rendezvous (But not an issue for EM or Solar Sail flyby of Mars because Landers aerobrake into Mars)
- **Comparison with Solar Sails for Mars Cargo Missions**

System	M2P2 Sail	MagSail	Solar Sail
Thrust (N/km^2 of Mag Field)	0.001	0.001	9
Hardware Dimensions	Small	60-100 km Dia.	4-5 km Dia.
Mass	Small	Large	Medium
	(3 MT)	(100 MT)	(60-75 MT)
Propellant Use	0.25 kg/Day/N	None	None
	(Isp=35,000s)		
Min. Ops Altitude	GTO (LEO ?)	Heliocentric	1000-2000 km
LEO->Ops V (km/s)	2.5	3.3	0.8
Acceleration (Ac)	Constant	$1/R^2$	$1/R^2$
	(Disk inflates as $1/R^2$)	(Fixed Size)	(Fixed Size)
Elect Power System	Yes	(Yes)	No
Tangential Thrust	Limited	Limited	Yes

M2P2 SAIL FOR THE MARS CARGO MISSION

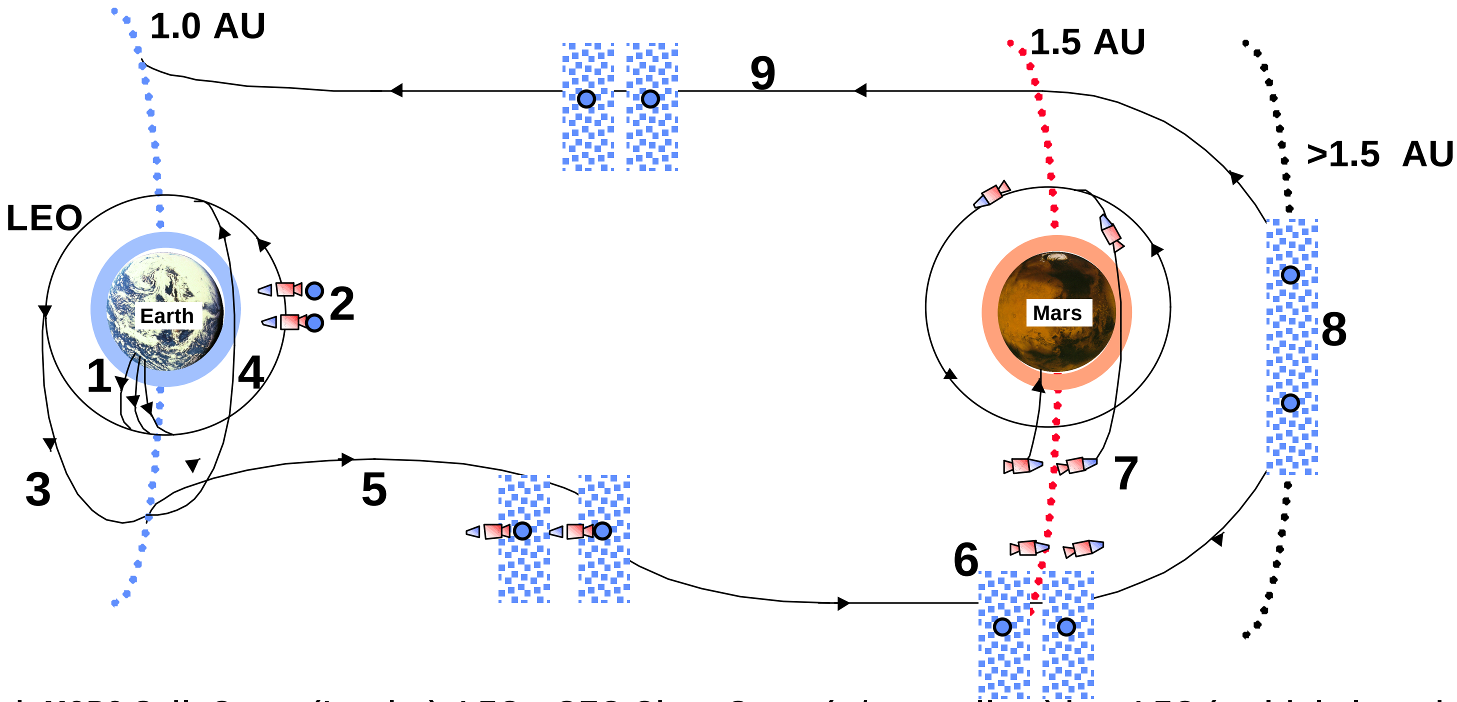
MISSION SCENARIO

- M2P2 mission starts in 400 km LEO (1 M2P2 required per Mars Lander)
- M2P2 plus Cargo (58-MT or 72-MT Mars Lander) boosted to GEO transfer orbit (GTO) by Chem Stage
  - May be possible to operate M2P2 directly from LEO, but may not be practical (I.e., excessive trip time, power)
- M2P2 (w/ payload) transfers to heliocentric Mars orbit/flyby (Vinfinity=0)
  - Lander w/Ascent Stage aerobrakes to Crew rendezvous orbit, Lander w/ Surface Hab. aerobrakes to surface (Eliminates need for M2P2 Mars capture)
- M2P2 (empty) returns to Earth orbit for re-use (optional)

M2P2 TRAJECTORY CALCULATIONS

- Trip times a function of Total Characteristic Acceleration (Ac, mm/s^2)
  - Ac = Thrust / Total (M2P2+Payload) Mass
    - Thrust = 0.001 N/km^2 of magnetic “wall” or disk area (treat area and corresponding thrust as free variables)
      - Power = 1 kWe per N of Thrust, Propellant Consumption = 0.25 kg/Day per Newton of Thrust
  - Heliocentric transfer calculated by Carl Sauer (JPL)
- <u>Total</u> IMLEO = M2P2 + Payload (Mars Lander) + Chem Stage + ETO Propellant Tankers (for Chem Stage and Mars Landers)

M2P2 SAIL CARGO MISSION EVENT SEQUENCE



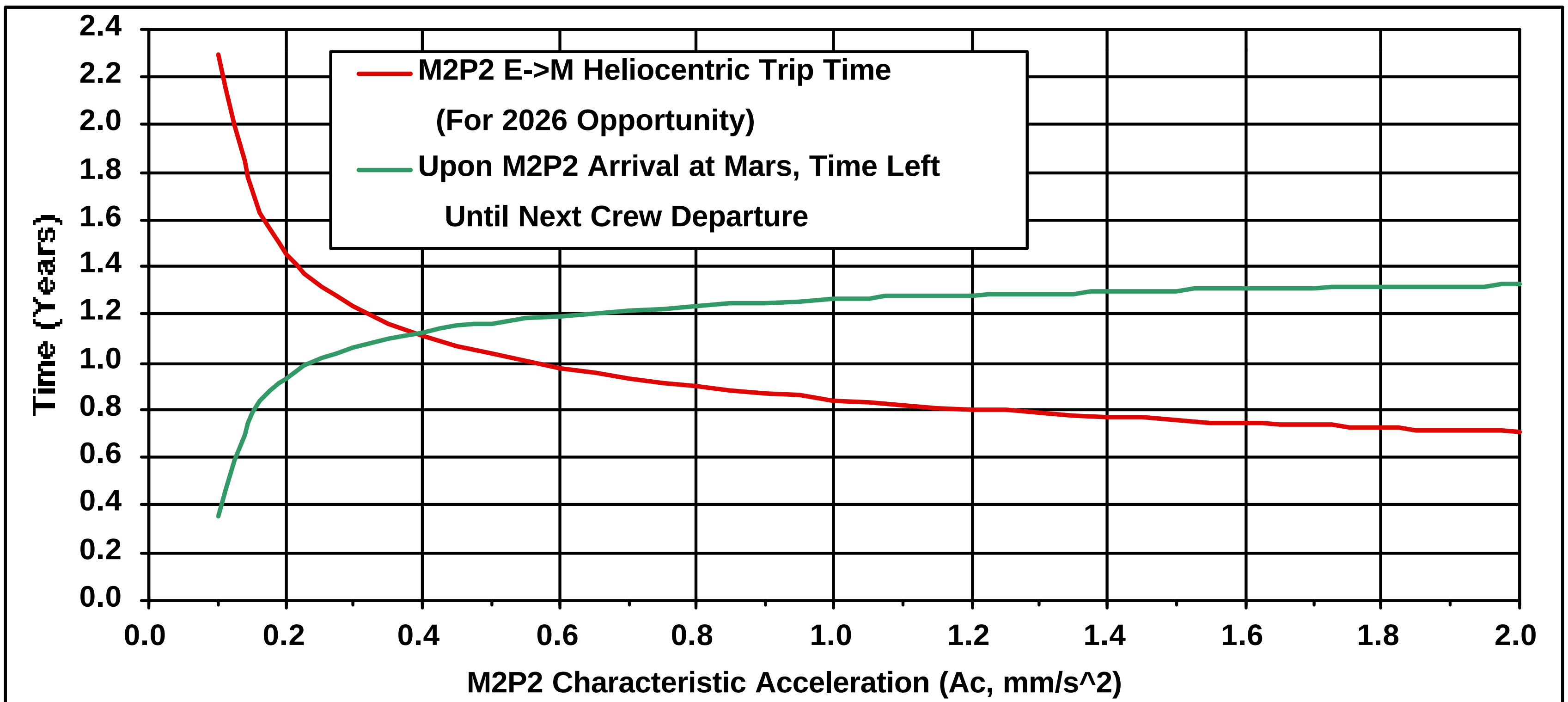
1. Launch 1-2 each M2P2 Sail, Cargo (Lander), LEO->GTO Chem Stage (w/ propellant) into LEO (multiple launches)
2. Assemble cargo vehicle systems (1-2 vehicles) by mating 1 Cargo with 1 M2P2 Sail
3. Use 1 each Chem Stage to transfer 1 each M2P2 Sail+Cargo vehicle into GTO orbit
4. Chem Stage returns to LEO with aerobraking
5. M2P2 Sails (w/ Cargo) perform Earth escape and heliocentric transfer to heliocentric 1.5 AU (Mars) orbit
6. Cargo (Landers) separate from M2P2 Sails on Mars approach (Vinfinity~0)
7. Landers aerobrake into Mars
   - Lander w/ Ascent Vehicle aerobrakes into Mars orbit to await rendezvous with Piloted vehicle
   - Lander w/ Surface Habitat aerobrakes to Mars surface
8. Depending on Ac and trajectory thrusting constraints, M2P2 Sails either loiter in Mars heliocentric orbit (to await Earth return opportunity), or perform a Mars flyby (to larger distance from Sun)
9. Depending on Ac and trajectory thrusting constraints, M2P2 Sails perform heliocentric transfer to heliocentric 1 AU (Earth) orbit

M2P2 SAIL CALCULATION METHODOLOGY

- Determine M2P2 heliocentric trip times as a function of Ac (for “worst” year 2026)
- Define M2P2 System
  - Free parameter: M2P2 electromagnetic “wall” size (100-500 km dia.) and area
  - Remaining M2P2 parameters depend on “wall” area and corresponding thrust
    - Thrust = 1 milli-N/km^2 of “wall” area
    - Propellant (H_2O) consumption = 0.25 kg/Day per N of Thrust (used to “inflate” the magnetic “wall”) - May be as high as 1 kg/Day, but propellant mass is still small compared to rest of vehicle (with Payload)
    - Electric Power = 1 kWe per N of Thrust
    - M2P2 Propulsion System (“thruster”) = 2 kg/kWe
  - Use “generic” Nuclear power system for electric power
    - Curve fit of Specific Mass = A*(Pe)^B for 0.25-kWe RTG at 200 kg/kWe and 100-kWe SP-100 at 30 kg/kWe
  - Propellant Tankage Factor (TF) = 0.11 (Water)
- Pick Payload mass (One 58-MT or one 72-MT Mars Lander per M2P2 Sail)
- Determine TOTAL (Sail+Payload) M2P2 vehicle Mass and corresponding Ac
  - Use trajectory data to determine Trip Time and Propellant consumption
    - Iterate Ac and Trip Time based on Propellant use
- Add LEO->GTO Chem Stage and Propellant Tankers for total Initial Mass in LEO (IMLEO)

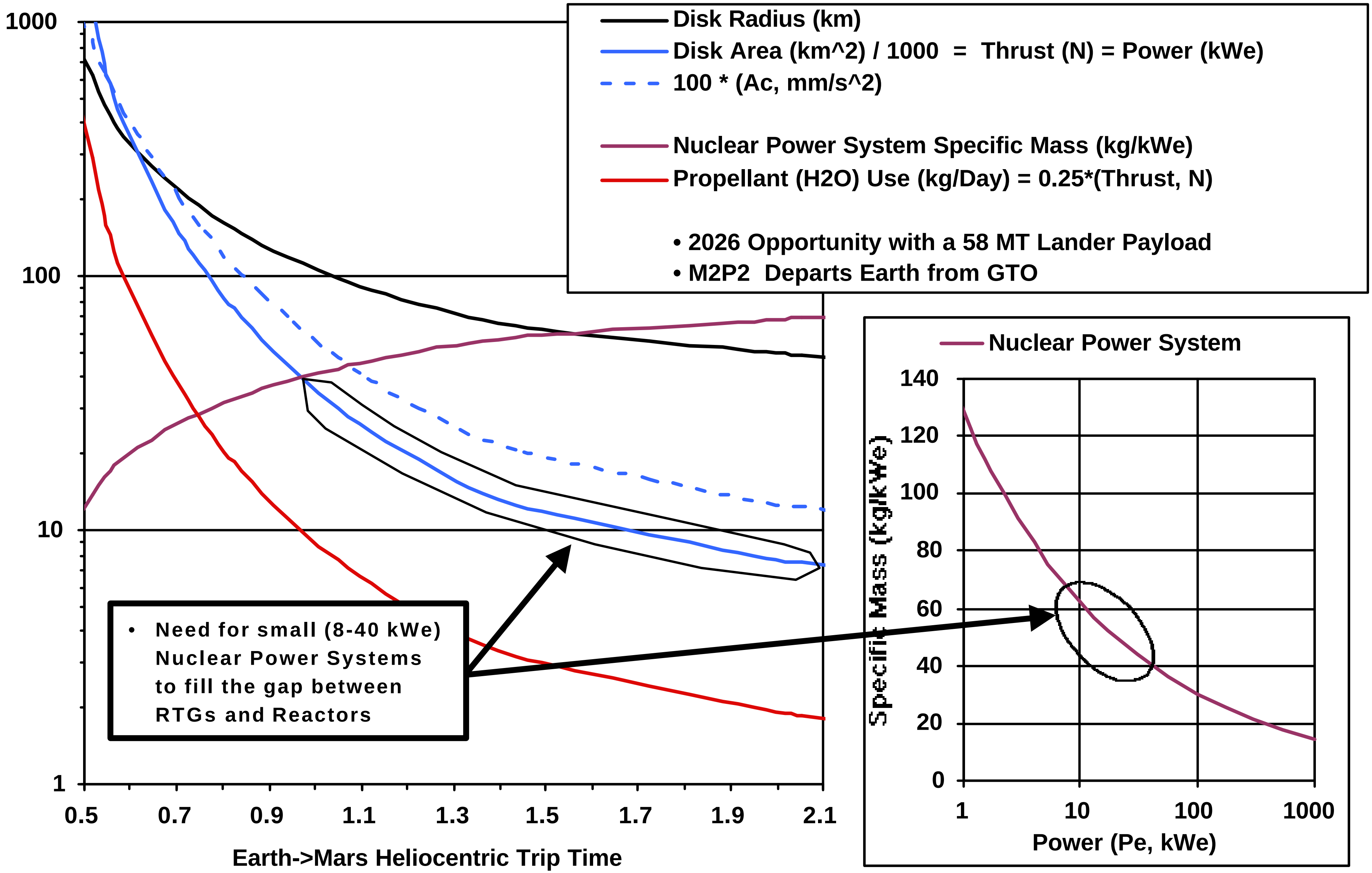
M2P2 SAIL HELIOCENTRIC TRIP TIME VS CHARACTERISTIC ACCELERATION (Ac)

- Could not obtain acceptable Earth-Mars trajectory code results for M2P2
  - Limited tangential thrust of M2P2 greatly complicates calculations for transfers between circular heliocentric orbits
- Approximated constant-thrust M2P2 with $1/R^2$ Solar Sail trajectory
  - Constant-thrust M2P2 Ac=0.342 mm/s^2 comparable to Solar Sail Ac=1 mm/s^2
  - This approximation will underestimate the trip time required because M2P2 has limited tangential thrust as compared to a Solar Sail
- Selected 2026 as "worst" year (based on Solar Sail trajectory results)
  - Need to have payload arrive at Mars prior to next Crew Earth departure



M2P2 SAIL SYSTEMS PARAMETERS

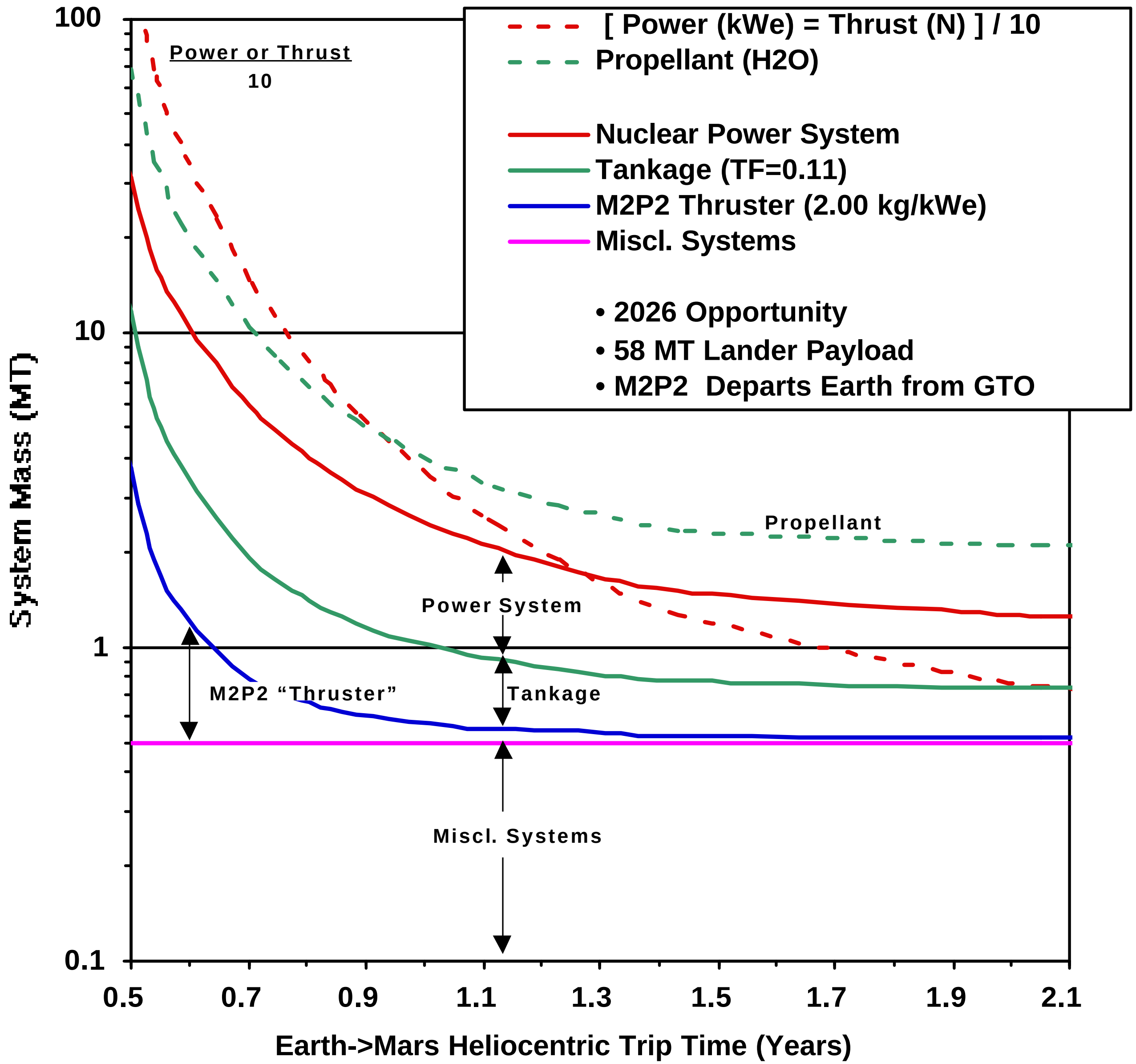
(58-MT Payload)



M2P2 SAIL SYSTEMS MASS BREAKDOWN

(58-MT Payload)

- M2P2 vehicle is very lightweight
- Mass dominated by propellant (water) and electric power system
  - M2P2 “Thruster” (plasma source) only 2 kg/kWe
- Need constant power
  - Solar-Electric: 15 kg/kWe at 1 AU scales to 34 kg/kWe at Mars
  - Power ranges from 8 kWe at 2 yrs. to 2.1 MWe at 0.5 Yr
    - Need for nuclear power systems in range of few 10s of kWe for many applications



CHEM LEO->GTO STAGE REQUIRED TO PLACE EM SAIL IN HIGH ORBIT

- Modeling by Winglee indicates that M2P2 can operate below Earth's magnetopause (10Re, 57,400 km altitude)
  - May be possible to operate directly from LEO, but current analysis requires operation from GEO transfer orbit (GTO)
  - Implies large V, and <u>heavy</u> Chem Stage (dominates IMLEO) for LEO->GTO

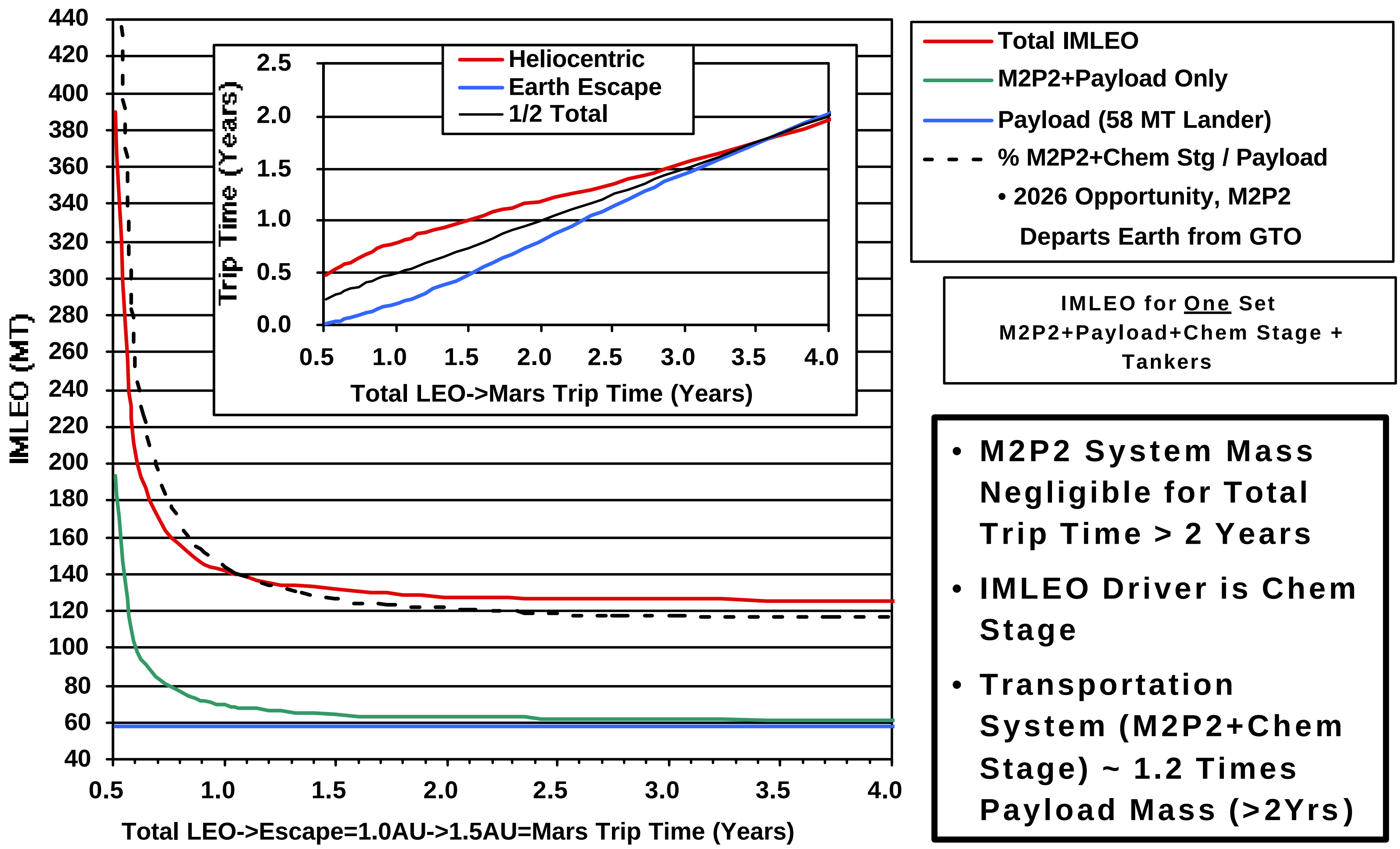
For 400-km LEO -->	GTO	GEO (ø=0)	MagPause	Lunar Orbit	C3=0	Mars Min Energy
Ideal V (km/s) =	2.4	3.9	4.0	3.9	3.2	3.5

- Assume Chem Stage for LEO->GTO (Stage aerobrakes back to LEO for re-use)
  - O2H2, Isp = 460 s, TF = 0.12, fixed mass components = 1.0 MT, ETO Tanker TF = 0.06
  - Aeroshell = 15% of wet stage pre-Aerobraking (A/B) entry
  - V Up = 2496 m/s = 2398 m/s (Ideal V) + 2% Ideal V (FPR) + 50 m/s (TCM, rendezvous & docking, etc.)
  - V Down (A/B) = 192 m/s = 139 m/s (Ideal V) + 2% Ideal V (FPR) + 50 m/s (TCM, etc.)
- Chem Stage can be high thrust (RL-10 class) - M2P2 doesn't have large deployed structures like Solar Sails
- Chem Stage mass dominates IMLEO, but still significantly lighter than all-Chem system

Example: (2 Yr E->M Trip Time)	<u>M2P2</u>	<u>All-Chem</u>
Payload (MT)	61.4 (M2P2+Lander)	58.0 (Lander)
Chem Stage (MT)	64.2 (LEO->GTO->LEO w/ A/B)	151.0 (LEO->C3=8.7->LMO w/ A/B)
IMLEO (MT)	125.6	209.0

M2P2 SAIL IMLEO VS TRIP TIME

(58-MT Payload)



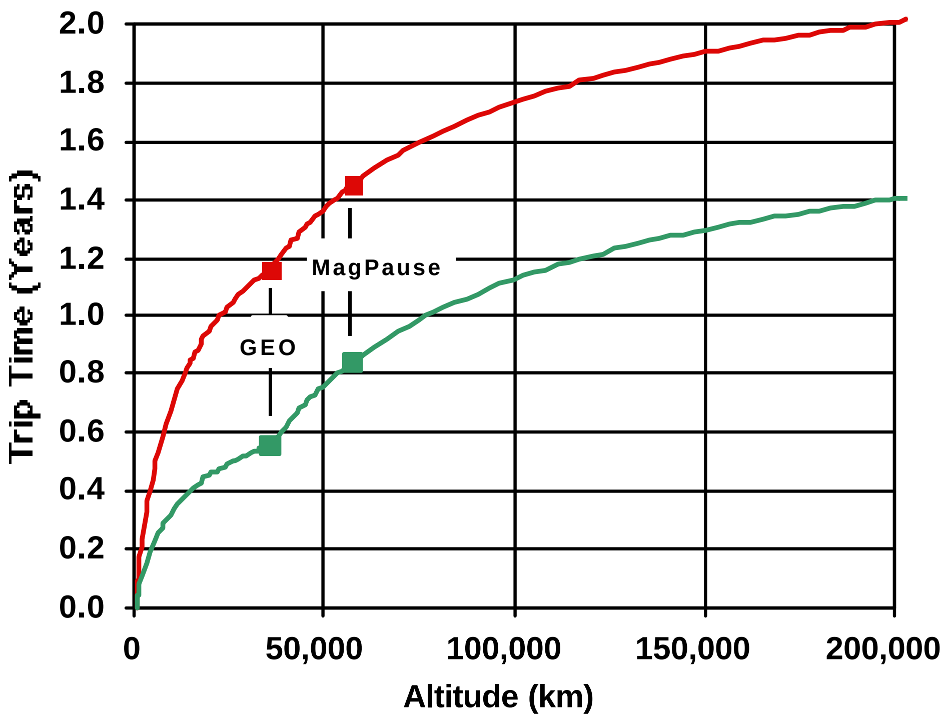
IMLEO for <u>One</u> Set M2P2+Payload+Chem Stage + Tankers

- M2P2 System Mass Negligible for Total Trip Time > 2 Years
- IMLEO Driver is Chem Stage
- Transportation System (M2P2+Chem Stage) ~ 1.2 Times Payload Mass (>2Yrs)

M2P2 OPERATION WITHIN THE EARTH'S MAGNETOSPHERE

- It <u>may</u> be possible to operate M2P2 within the Earth's magnetosphere directly from LEO
- However, for small, low power M2P2, this gives a prohibitively slow, low-thrust spiral
  - Trade fast, heavy high-thrust LEO/GTO->C3=0 from Chem stage against a very slow, very light Direct-LEO->C3=0 M2P2 low-thrust escape spiral

	LEO->C3=0	Wet Stage (MT)	Payload (MT)	IMLEO (MT)	Trip Time (Years)
Fast/Heavy	Chem Stage	96.6	60.6 (M2P2+Lander)	157.2	<0.1 (+2.0 Yrs C3=0->Mars)
Slow/Light	M2P2	3.6	58.0 (Lander Only)	61.6	2.7 (+2.0 Yrs C3=0->Mars)

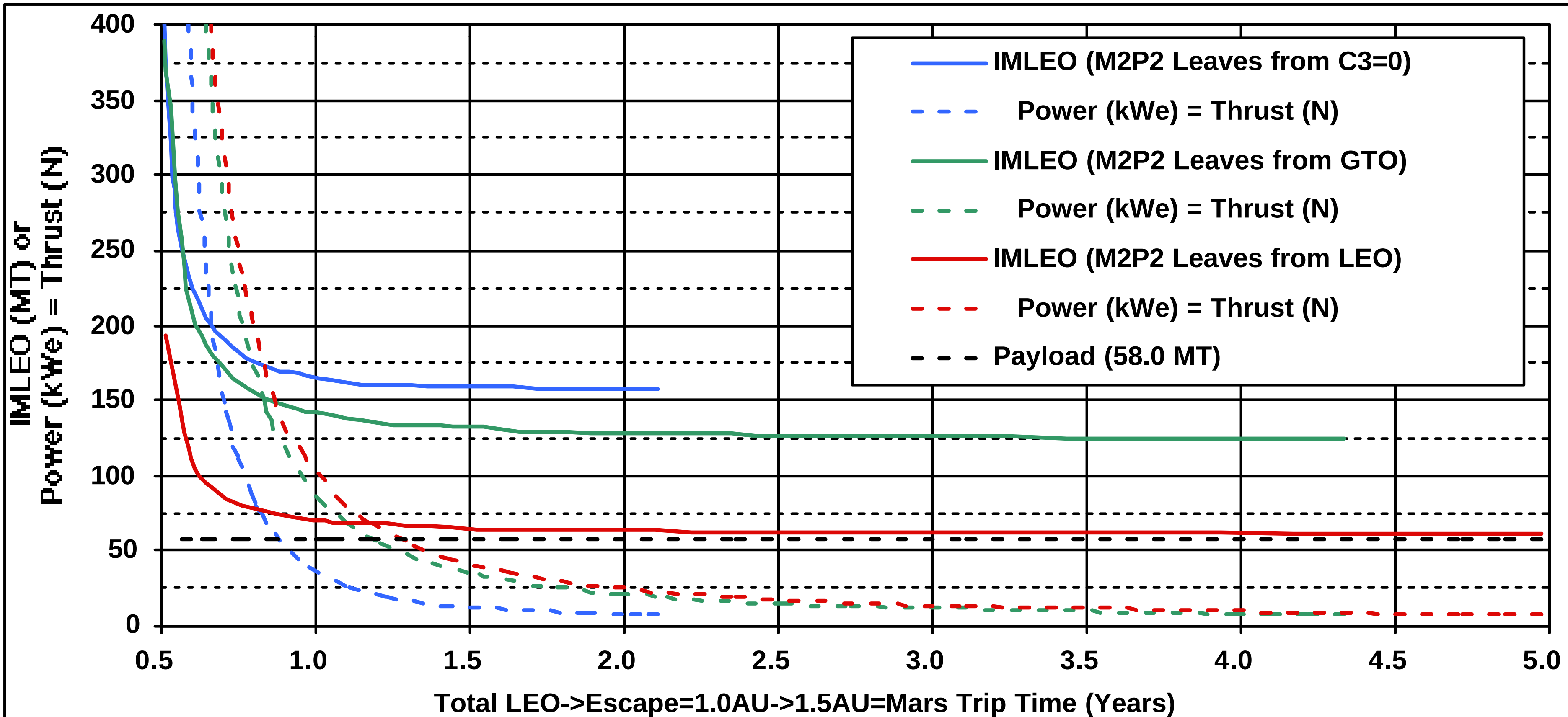


<u>LEO->Escape Trip Time</u>
<u>GTO->Escape Trip Time</u>
<u>1.0->1.5 AU Heliocentric System Parameters</u>
Trip Time = 2.0 Years, Payload = 58.0 MT
Mo = 60.6 MT, Mp = 1.4 MT
F (N) = Pe (kWe) = 7.70
M-DOT = 1.92 kg/Day, Isp = 35,265 s
<u>LEO/GTO->Escape Planetocentric System Parameters</u>
LEO->Escape: Mo = 61.6 MT, Mp = 0.9 MT
GTO->Escape: Mo = 61.4 MT, Mp = 0.7 MT

- LEO/GTO->GEO Spiral (F = 7.70 N)
  M-DOT = 0.5 * Heliocentric Value, Isp = 70,531 s
  Duty Cycle = 1.0 (Magnetic Buoyancy)
- GEO->MagnetoPause Spiral (F = 7.70 N)
  M-DOT = 0.5 * Heliocentric Value, Isp = 70,531 s
  Duty Cycle = 0.5 (Orbit Phasing)
- MagnetoPause->Escape Spiral (F = 7.70 N)
  M-DOT = 1.0 * Heliocentric Value, Isp = 35,265 s
  Duty Cycle = 0.5 (Similar to Solar Sail)

M2P2 OPERATION WITHIN THE EARTH'S MAGNETOSPHERE - CONT'D

- M2P2 can achieve reasonable trip times without the need for a Chem Stage, <u>IF</u> operation directly from LEO is possible, and <u>IF</u> high-power (> 10s of kWe) operation is acceptable
  - <u>Very</u> low IMLEO (little M2P2 propellant needed for Earth escape or heliocentric transfer)
  - Will need disposable reactor (no obvious way to enter Mars orbit or return to Earth orbit) - Could add conventional electric propulsion system to capture at Mars or Earth, but IMLEO penalty (EP thruster Isp ~1/7 that of M2P2)
    - Add extra M2P2 propellant for deep space reactor disposal (solar system escape ?)



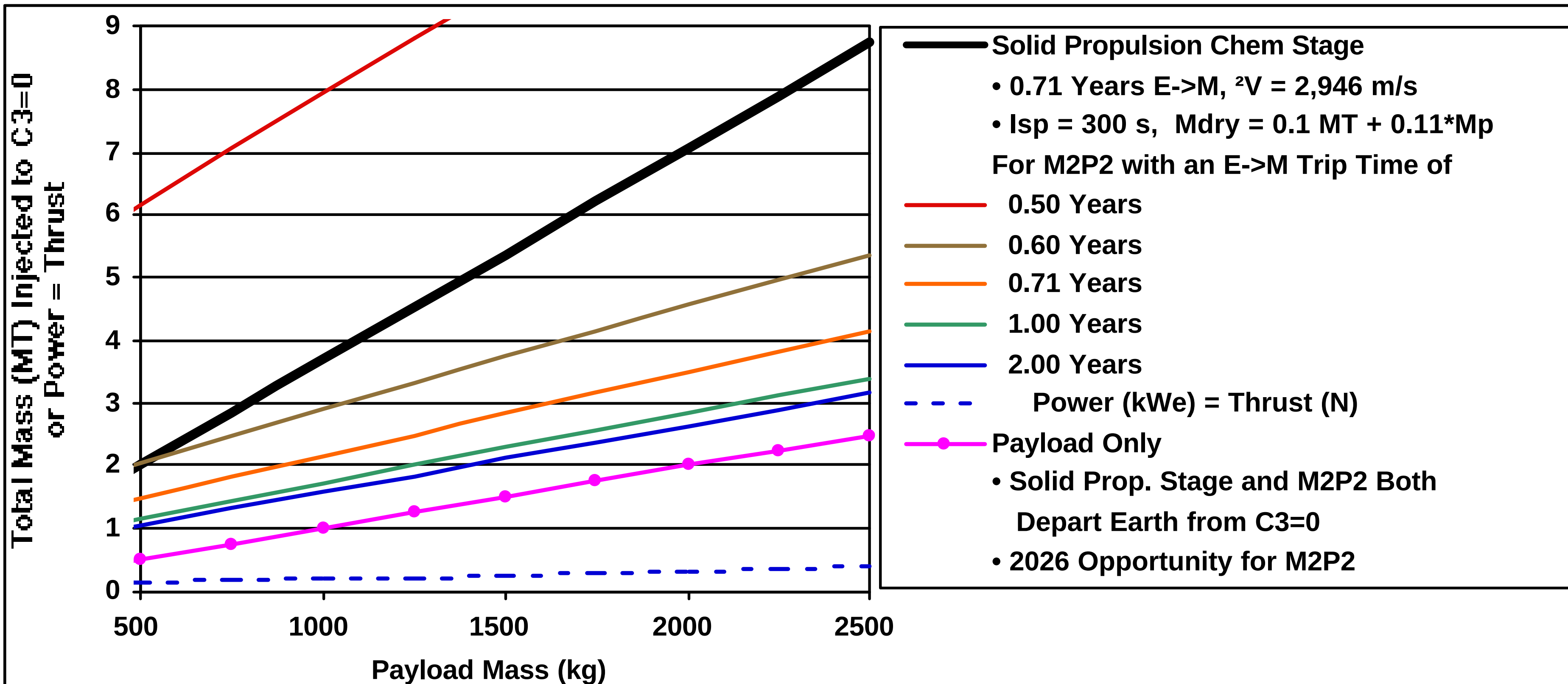
SUMMARY FOR M2P2 SAILS

- M2P2 Sails may not be attractive for a Mars Cargo transportation system
  - Need for a LEO->GTO or C3=0 Chem Stage adversely impacts IMLEO
    - Using a high-Isp Stage (M2P2, SEP/NEP, etc.) for Earth escape could reduce IMLEO, but only at expense of greatly increased trip time or power
  - Earth orbit raising feasibility TBD, but orbit lowering appears possible
    - Difficult to simulate in lab - may need flight expt. to demonstrate (GTO piggyback?)
  - Potentially reusable - However, this depends on ability to modulate thrust vector (tangential vs radial) to return to Earth (or, more generally, to go into a circular heliocentric orbit)
    - Need to modify/improve low-T/W trajectory codes to handle M2P2
  - Low thrust (but high effective Isp ~ 35,000 s) results in long trip times (same problem as Solar Sails)
    - May be easier to reduce M2P2 trip time (add more power) than for Solar Sails (make sail bigger)

- Although M2P2 may not be attractive for Piloted or Cargo Mars missions, there are a number of robotic missions that could benefit from this technology
  - Small systems sizes (dimensions, mass, power) lend themselves to scale-down for robotic spacecraft
  - Generally good candidate for outer-planet or interstellar precursor missions (make use of radial thrust component)
    - Aerobrake or "Magnetobrake" capture for outer-planet orbiters
  - Major technology feasibility issues being addressed in NIAC-funded research

EXAMPLE OF M2P2 SCALING FOR ROBOTIC MARS MISSIONS

- **Compare M2P2 vs Chem Stage injection from C3=0 to C3=8.7 (Hohmann)**
  - **Spin-stabilized solid propellant Chem Stage, Isp = 300 s, V = 2.946 km/s, 259 day = 0.71 year trip time**
  - **Nuclear power M2P2, Isp = 35,000 s, 2026 trajectory**
  - **Payload does its own Mars orbit insertion (aerobrake/prop)**
- **High Isp of M2P2 combined with excellent scalability to small sizes provides benefits at modest payload sizes**



CATEGORIZING M2P2

- M2P2 is a new, novel propulsion concept - where does it fit ?

- In one sense, M2P2 acts like a high-Isp electric propulsion system
  - SEP with solar arrays (because electric power drops off as $1/R^2$)
  - NEP with nuclear-electric power (constant thrust)
  - Interestingly, can use almost any propellant (Ar, H_2, H_2O, CO_2, . . .)
    - Possible unconventional propellant resources:
      - Extraterrestrial resource utilization: H_2O from Phobos
      - Crew biowaste gasses: CO_2

- In another sense, M2P2 acts like a fusion propulsion system with a "Gain" of (Jet Power Out) / (Electric Power In) = 173
  - For 1 N of thrust, Pe = 1 kWe, 0.25 kg/Day, and Isp = 35,265 s
  - Effective Jet Power (derived from the solar wind power impacting the M2P2 magnetic "bubble" to produce thrust) =

    $P_j = 1/2\ G_c\ I_{sp}\ F = 172.8$ kW
  - This represents remarkable leverage for such a small system

BACKUP MATERIAL

SOLAR SAILS

- Sail Trip Time & IMLEO for Payload = Heavy (72-MT) Lander
- Mission Timeline & IMLEO, and L/V Manifests for Payload = Ascent/Descent (HMO) and Descent/Long Stay Hab. Landers

M2P2 SAILS

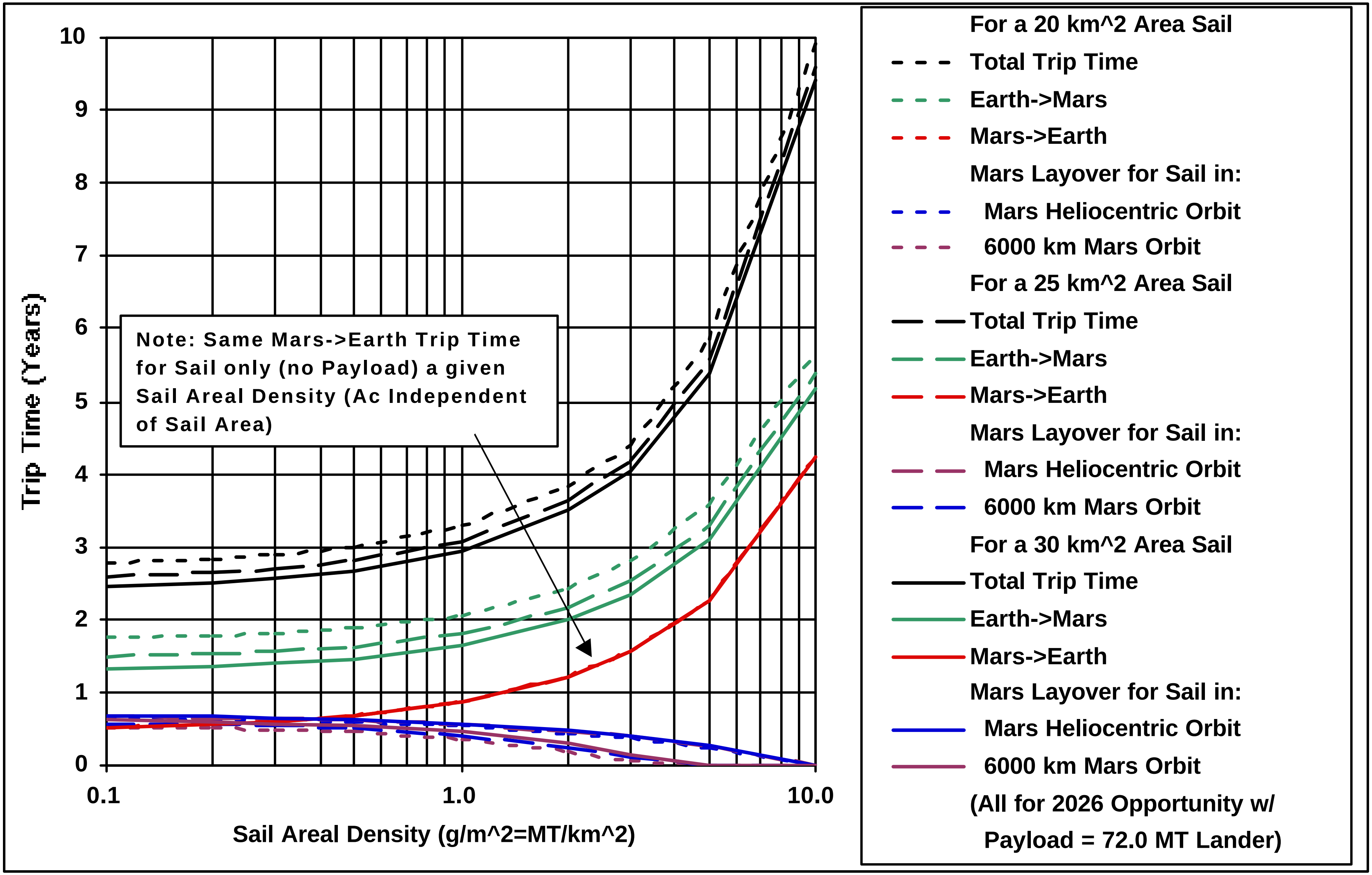
- Results for 72-MT Payload case
- M2P2 Operation Within the Earth's Magnetosphere

GENERAL

- Chemical Propulsion Tankage Factor Assumptions

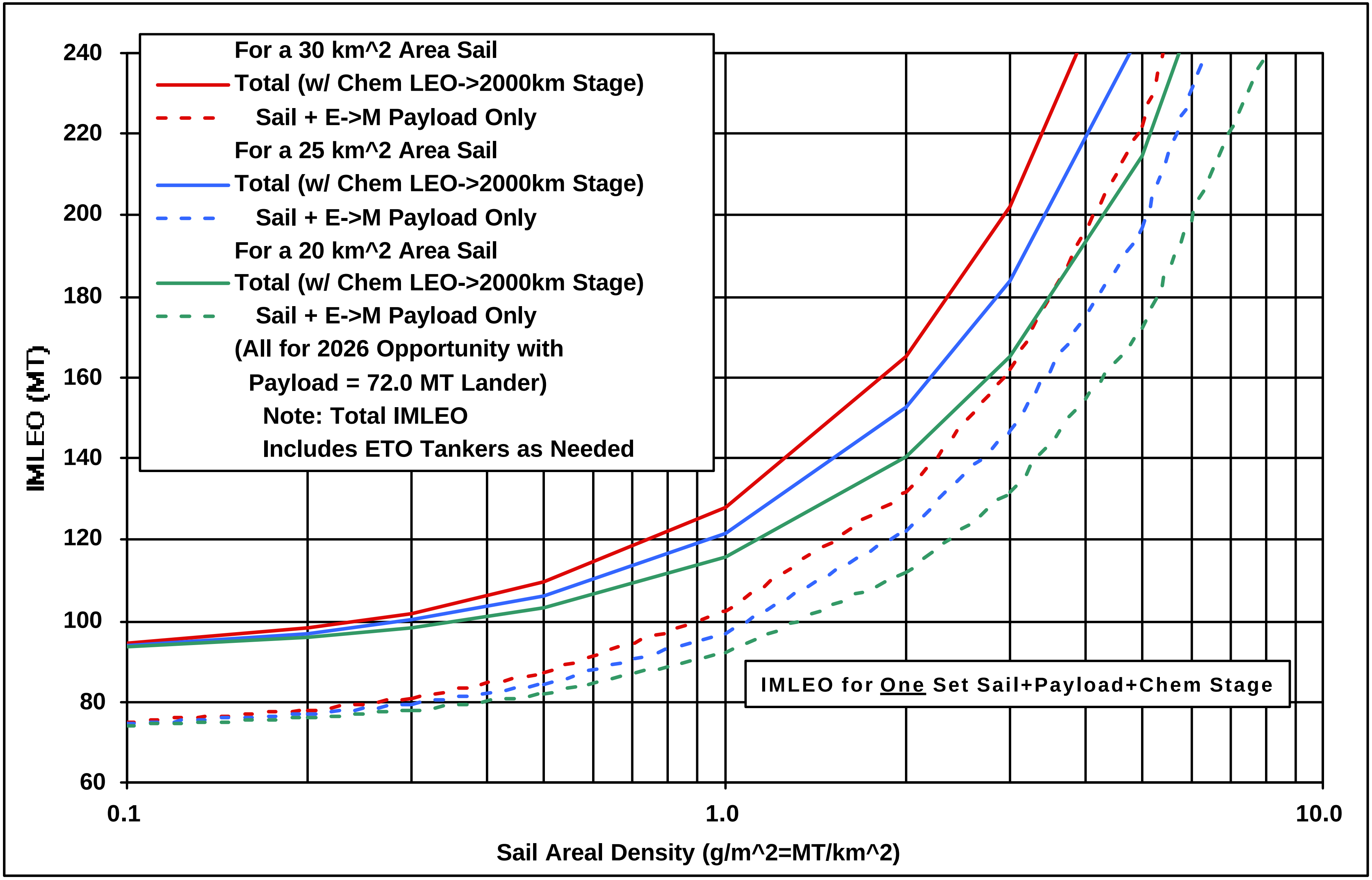
SOLAR SAIL TRIP TIME VS AREAL DENSITY

(AS A FUNCTION OF SAIL AREA FOR 72-MT PAYLOAD)



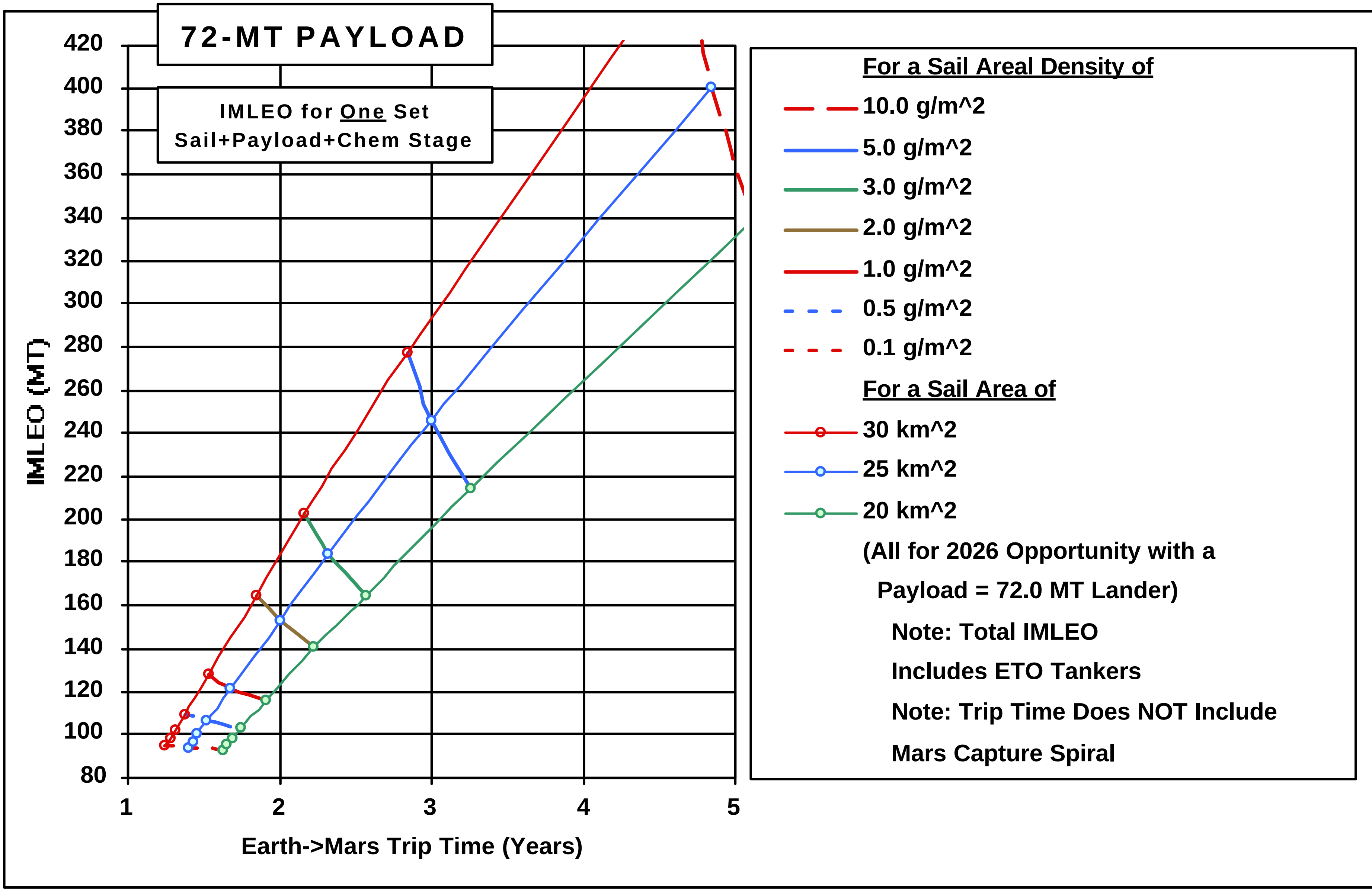
SOLAR SAIL IMLEO VS AREAL DENSITY

(AS A FUNCTION OF SAIL AREA FOR 72-MT PAYLOAD)



SOLAR SAIL IMLEO VS TRIP TIME

(AS A FUNCTION OF SAIL AREA & AREAL DENSITY)



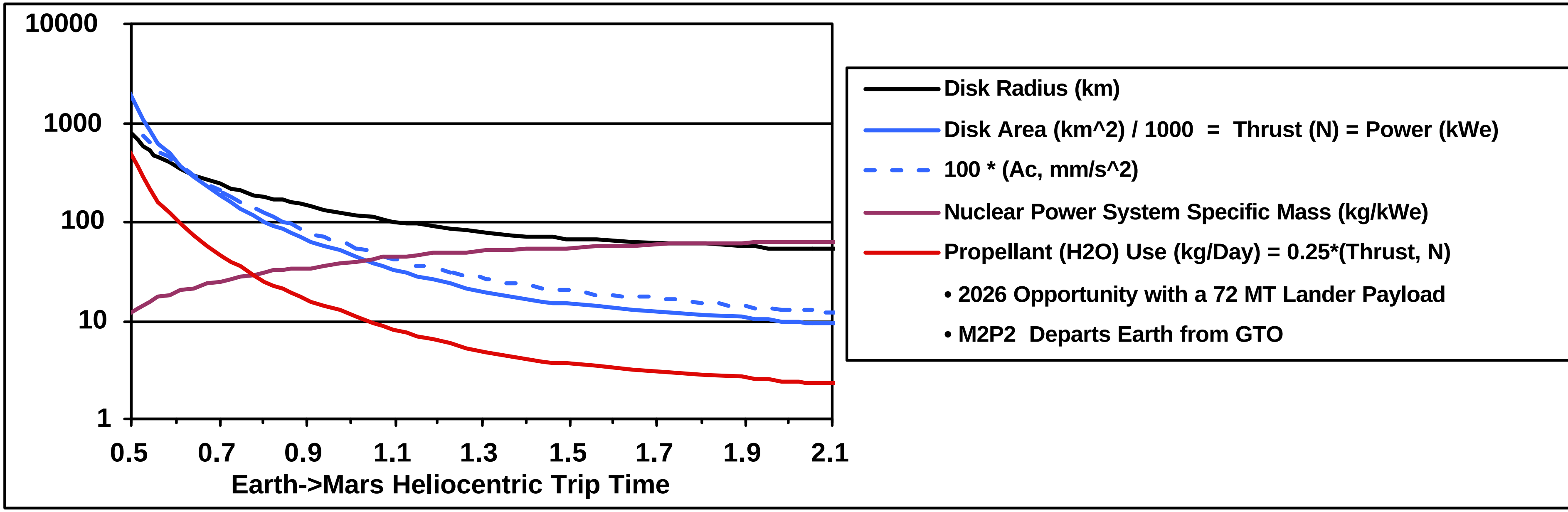
SOLAR SAIL SYSTEM TIMELINE AND MASS EXAMPLE (58.2 MT PAYLOAD)

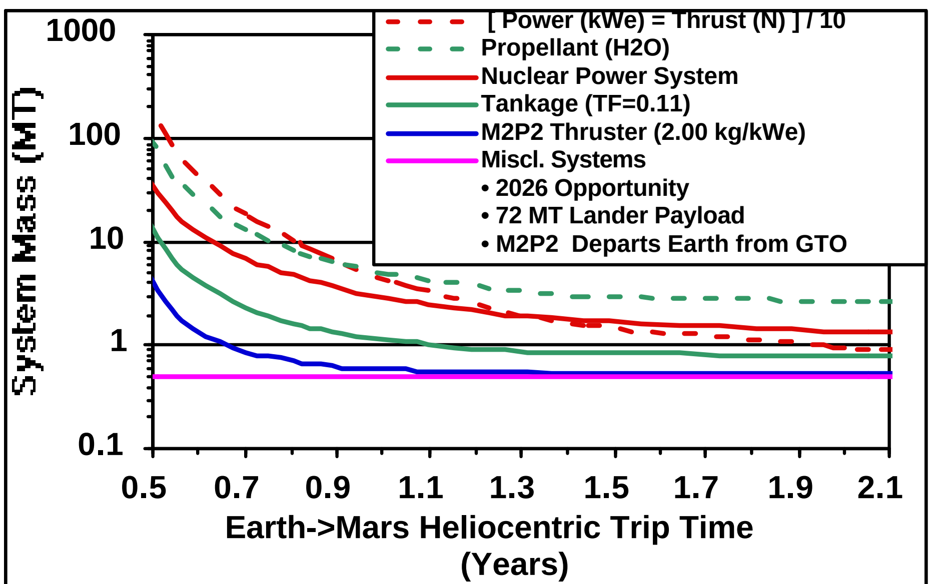
20-km^2, 3.0-g/m^2 Sails, 58.237-MT Descent w/ Long-Stay Hab Lander	DATE	IMLEO	(MT)
• Setup for First Mars Opportunity	10/24/2014	Sail	60.0
• First set of Sail and Lander launched into LEO	(L1 - 60 Days)	Lander (Wet)	58.2
• Chem Stage launched into LEO		Lander Tanker (Dry)	0.6
• Lander & Chem Stage Tankers (Wet) launched into LEO		Chem Stage (Dry)	3.9
• Sail deployed, Sail+Lander transported to 2000 km		Chem Propellants	24.5
• Chem Stage returns to LEO for re-use		Chem Tanker (Dry)	1.5
	Subtotal	148.8	
• First Mars Opportunity (L1)	L1		
• First set of Sail+Lander departs Earth	12/23/2014		
• Setup for Second Mars Opportunity	01/01/2017	Sail	60.0
• Second set of Sail and Lander launched into LEO	(L2 - 60 Days)	Lander (Wet)	58.2
• Lander & Chem Stage Tankers (Wet) launched into LEO		Lander Tanker (Dry)	0.6
• Sail deployed, Sail+Lander transported to 2000 km		Chem Propellants	24.5
• Chem Stage returns to LEO for re-use		Chem Tanker (Dry)	1.5
	Subtotal	144.8	
• First set of Sail+Lander arrives at Mars	02/27/2017		
• Lander aerobrakes into required orbit	(Crew Departure - 473 Days)		
• Second Mars Opportunity (L2)	L2		
• Second set of Sail+Lander departs Earth	03/02/2017		
• Crew departs Earth	06/15/2018		
• First set of Sail returns to Earth (2000 km orbit)	03/07/2019	Lander (Wet)	58.2
• Setup for Third Mars Opportunity	(L3 - 59 Days)	Lander Tanker (Dry)	0.6
• Lander, Lander & Chem Stage Tankers launched into LEO		Chem Propellants	12.9
• Lander transported to 2000 km, attached to Sail		Chem Tanker (Dry)	0.8
• Chem Stage returns to LEO for re-use		Subtotal	72.6
• Second set of Sail+Lander arrives at Mars	04/22/2019		
• Lander aerobrakes into required orbit	(Crew Departure - 237 Days)		
• Third Mars Opportunity (L3)	L3		
• First set of Sail+Lander departs Earth	05/05/2019		
• Crew departs Earth	12/15/2019		
• Second set of Sail returns to Earth (2000 km orbit)	05/11/2021	Lander (Wet)	58.2
• Setup for Fourth Mars Opportunity	(L4 - 39 Days)	Lander Tanker (Dry)	0.6
• Lander, Lander & Chem Stage Tankers launched into LEO		Chem Propellants	12.9
• Lander transported to 2000 km, attached to Sail		Chem Tanker (Dry)	0.8
• Chem Stage returns to LEO for re-use		Subtotal	72.6
• First set of Sail+Lander arrives at Mars	08/14/2021		
• Lander aerobrakes into required orbit	(Crew Departure - 185 Days)		
• Fourth Mars Opportunity (L4)	L4		
• Second set of Sail+Lander departs Earth	06/20/2021	Total for 4 Cargo Missions	438.7
• Crew departs Earth	02/15/2022	Ave. per Cargo Mission	109.7

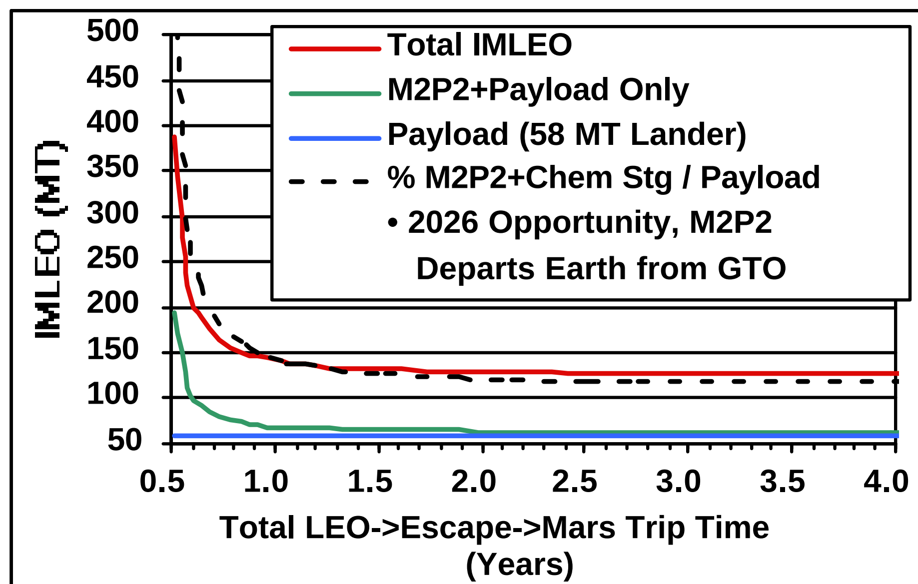
SOLAR SAIL SYSTEM TIMELINE AND MASS EXAMPLE (72.1 MT PAYLOAD)

25-km^2, 3.0-g/m^2 Sails, 72.140-MT Descent/Ascent (HMO) Lander	DATE	IMLEO	(MT)
• Setup for First Mars Opportunity	10/27/2014	Sail	75.0
• First set of Sail and Lander launched into LEO	(L1 - 60 Days)	Lander (Wet)	72.1
• Chem Stage launched into LEO		Lander Tanker (Dry)	1.5
• Lander & Chem Stage Tankers (Wet) launched into LEO		Chem Stage (Dry)	4.6
• Sail deployed, Sail+Lander transported to 2000 km		Chem Propellants	30.4
• Chem Stage returns to LEO for re-use		Chem Tanker (Dry)	1.8
		Subtotal	185.4
• First Mars Opportunity (L1)	L1		
• First set of Sail+Lander departs Earth	12/26/2014		
• Setup for Second Mars Opportunity	01/04/2017	Sail	75.0
• Second set of Sail and Lander launched into LEO	(L2 - 60 Days)	Lander (Wet)	72.1
• Lander & Chem Stage Tankers (Wet) launched into LEO		Lander Tanker (Dry)	1.5
• Sail deployed, Sail+Lander transported to 2000 km		Chem Propellants	30.4
• Chem Stage returns to LEO for re-use		Chem Tanker (Dry)	1.8
		Subtotal	180.8
• First set of Sail+Lander arrives at Mars	02/26/2017		
• Lander aerobrakes into required orbit	(Crew Departure - 473 Days)		
• Second Mars Opportunity (L2)	L2		
• Second set of Sail+Lander departs Earth	03/05/2017		
• Crew departs Earth	06/15/2018		
• First set of Sail returns to Earth (2000 km orbit)	03/07/2019	Lander (Wet)	72.1
• Setup for Third Mars Opportunity	(L3 - 62 Days)	Lander Tanker (Dry)	1.5
• Lander, Lander & Chem Stage Tankers launched into LEO		Chem Propellants	15.9
• Lander transported to 2000 km, attached to Sail		Chem Tanker (Dry)	1.0
• Chem Stage returns to LEO for re-use		Subtotal	90.4
• Second set of Sail+Lander arrives at Mars	04/22/2019		
• Lander aerobrakes into required orbit	(Crew Departure - 237 Days)		
• Third Mars Opportunity (L3)	L3		
• First set of Sail+Lander departs Earth	05/08/2019		
• Crew departs Earth	12/15/2019		
• Second set of Sail returns to Earth (2000 km orbit)	05/11/2021	Lander (Wet)	72.1
• Setup for Fourth Mars Opportunity	(L4 - 42 Days)	Lander Tanker (Dry)	1.5
• Lander, Lander & Chem Stage Tankers launched into LEO		Chem Propellants	15.9
• Lander transported to 2000 km, attached to Sail		Chem Tanker (Dry)	1.0
• Chem Stage returns to LEO for re-use		Subtotal	90.4
• First set of Sail+Lander arrives at Mars	08/14/2021		
• Lander aerobrakes into required orbit	(Crew Departure - 185 Days)		
• Fourth Mars Opportunity (L4)	L4		
• Second set of Sail+Lander departs Earth	06/22/2021	Total for 4 Cargo Missions	547.1
• Crew departs Earth	02/15/2022	Ave. per Cargo Mission	136.8

M2P2 SAIL RESULTS (72-MT PAYLOAD)







M2P2 OPERATION WITHIN THE EARTH'S MAGNETOSPHERE

- Discussions with Dr. Winglee indicate that M2P2 can be used for Earth orbit lowering within the ionosphere (below the magnetopause) using magnetobraking (analogous to electrodynamic tethers)
- Orbit raising using "magnetic buoyancy" also appears possible
- Several interesting characteristics described by Dr. Winglee:
  - Within the ionosphere, may have lower propellant consumption (and corresponding higher Isp) for a given thrust
  - Below GEO, can have continuous thrust, but above GEO, can thrust only 1/2 of orbit due to orbit phasing (analogous to solar sail orbit raising)
  - Calculations of Earth orbit raising shown earlier assumed:
    - LEO/GTO->Magnetopause: Effective propellant consumption 1/2 that of heliocentric (i.e., altitude > magnetopause) transfer value; Isp thus 2 x that of heliocentric
      - This reduces total propellant mass, but has no effect on trip time because propellant mass flow rate (M-DOT) also decreases
    - LEO/GTO->GEO continuous thrust, but GEO->escape thrust 1/2 of time (so trip time doubled for this portion)

CHEMICAL PROPULSION SYSTEM TANKAGE FACTOR ASSUMPTIONS

- **Tankage Factor (TF) = (Dry Mass of tanks, etc.) / (Propellant Mass [Mp])**
  - **Used to size Chem Stage and ETO Propellant Tankers for Chem Stage and Landers**
- **Various factors derived from Dennis G. Pelaccio, SAIC**

System			Chem Stage at O/F = 6.0	Chem Stage Space	Lander Tanker at O/F = 4.0	Chem Stage Tanker	Chem Stage Tanker Space	
Propellants	LH2	LO2	LO2/LH2	Storable	LO2/LCH4 (4)	LO2/LH2	Storable	Equation
Dry Tanks	0.110	0.020	0.033	0.030	0.0220	0.033	0.030	* Mp
Miscl Prop (1)	0.400	0.400	0.400	0.400	0.400	0.400	0.400	* Mdry tanks
Total Dry Prop	0.154	0.028	0.046	0.042	0.031	0.046	0.042	* Mp
Total Wet Prop	1.154	1.028	1.046	1.042	1.031	1.046	1.042	* Mp
Systems (2)	0.045	0.045	0.045	0.045	0.000	0.000	0.000	* (Total Wet Prop * Mp)
Total Dry	0.206	0.074	0.093	0.089	0.031	0.046	0.042	* Mp
Margin (3)	0.200	0.200	0.200	0.200	0.200	0.200	0.200	* (Total Dry * Mp)
Total Dry w/ Margin	0.247	0.089	0.112	0.107	0.037	0.055	0.050	* Mp

Comments:
(1) Additional propulsion system weight factor (lines, pressurant control system, tank mounts, etc.): 40% total dry propellant tank weight
(2) Avionics/communication scale factor: 4.5% of vehicle wet mass (includes vehicle control scaling effects)
(3) Vehicle dry weight design margin factor: 20% of total vehicle nominal dry design weight
(4) LCH4 defined as "Space Storable"